Minnesota Department of Transportation

RESEARCH SERVICES

Office of Policy Analysis, Research & Innovation

Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads

Eddie Johnson, Primary Author
Minnesota Department of Transportation

May 2013

Research Project
Final Report 2013-15

LRRB
LOCAL ROAD RESEARCH BOARD

Your Destination...Our Priority

To request this document in an alternative format, please contact the Affirmative Action Office at 651-366-4723 or 1-800-657-3774 (Greater Minnesota); 711 or 1-800-627-3529 (Minnesota Relay). You may also send an e-mail to ADArequest.dot@state.mn.us.

(Please request at least one week in advance).

Technical Report Documentation Page

1. Report No.
MN/RC 2013-15

2.

3. Recipients Accession No.

4. Title and Subtitle
Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads

5. Report Date
May 2013

6.

7. Author(s)
Eddie Johnson, Mark Watson, Roger Olson, Ki Hoon Moon, Mugurel Turos, and Mihai Marasteanu

8. Performing Organization Report No.

9. Performing Organization Name and Address
Minnesota Department of Transportation
395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

10. Project/Task/Work Unit No.

11. Contract (C) or Grant (G) No.
LRRB 889

12. Sponsoring Organization Name and Address
Minnesota Department of Transportation
Research Services
395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/201315.pdf

16. Abstract (Limit: 250 words)

This report summarizes lessons learned about the field performance of local roads containing Recycled Asphalt Pavement (RAP) and associated field and laboratory work with asphalt activation as well as the design and performance testing of high-RAP bituminous mixtures.

Transverse cracking performance of Minnesota county highways averaging 20-26% RAP was improved when PG 52-34 binder was selected over PG 58-28 or other binder grades.

Testing of the activation of RAP asphalt binder in plant and laboratory settings showed that coarse aggregates from plant mixing achieved a more uniform coating and were subjected to less abrasion than those from laboratory mixing.

Low temperature testing of laboratory mixture designs containing up to 55% RAP, and new-to-total asphalt cement ratios as low as 43%, found that indirect tensile test (IDT) creep stiffness increased along with RAP content. IDT critical temperature results showed that the addition of RAP significantly increased the critical temperature, predicting less crack resistance. Semi-circular bend fracture testing showed that the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, and the highest RAP contents had the most reduced fracture performance.

17. Document Analysis/Descriptors
Recycled Asphalt Pavement (RAP), Recycled materials, Binder Activation, Bituminous binders, SCB fracture, IDT creep, IDT strength, Tensile tests, Bend tests

18. Availability Statement
No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)
Unclassified

20. Security Class (this page)
Unclassified

21. No. of Pages
83

22. Price

Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads

Final Report

Prepared by:

Eddie Johnson
Mark Watson
Roger Olson

Minnesota Department of Transportation

Mihai Marasteanu
Ki-Hoon Moon
Mugurel Turos

Department of Civil Engineering
University of Minnesota

May 2013

Published by:

Minnesota Department of Transportation
Research Services
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155

Acknowledgments

This project was made possible with the support, expertise, and other contributions provided by the Minnesota Local Road Research Board, the project technical committee, the Asphalt Pavement Testing Laboratory at the University of Minnesota Twin Cities, personnel with Mathy Construction's Crane Creek Asphalt Plant, and the MnDOT Bituminous Office Trial Mix Laboratory.

Table of Contents

List of Figures

List of Tables

Executive Summary

This report summarizes lessons learned about the field performance of local roads containing Recycled Asphalt Pavement (RAP) and associated field and laboratory work with asphalt activation as well as the design and performance testing of high-RAP bituminous mixtures.

The major outcomes were:

This investigation of high RAP asphalt mixtures included collaborative research among county and state road agencies, the asphalt paving industry, and academia. For the purpose of this investigation, the term “high RAP” refers to mixtures having 30 percent RAP or more. The following outcomes were determined for the major objectives of the investigation.

Pavement performance of Minnesota county highways containing an average of 20 to 26 percent RAP showed that a 40 percent improvement occurred in transverse cracking per mile along with a 34 percent improvement in crack spacing when low PG -34 asphalt binder was used instead of low PG -28.

Asphalt binder activation was investigated with RAP and virgin aggregate mixtures produced in a batch plant and in the laboratory. No asphalt binder was added to the blends during production. It was found that coarse aggregates from plant mixing achieved a more uniform coating and were subjected to less abrasion than those from laboratory mixing. Temperature, mixing time, and heating time of RAP were the most influential parameters for complete coating. The percentage of RAP was an important variable in explaining the amount of partial coating.

Eight mixture designs were produced for laboratory evaluations. The designs used PG 58-28 and PG 58-34 asphalt binders with RAP contents ranging from 0 to 55 percent. Indirect tensile (IDT) and semi-circular bend (SCB) testing were performed at the low temperatures. IDT results showed that creep stiffness increased along with RAP content. RAP mixtures had slightly higher IDT strength values than non-RAP mixtures, except for the 58-34 binder mixtures tested at PG temperature. IDT critical temperature (Tcr) analysis showed that the addition of RAP significantly increased the critical temperature for the PG 58-34 binder, predicting less crack resistance. SCB fracture testing showed that the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, and the highest RAP content appeared to have the most reduced fracture performance.

Chapter 1. Introduction

Local Road Research Board (LRRB) project number 889, titled, “Study of High Recycled Asphalt Pavement (RAP) Asphalt Mixtures was sponsored by the Minnesota Local Road Research Board. The project included: surveys of local road performance, study of asphalt activation in the plant and lab, and the design and testing of high-RAP laboratory mixtures.

Background and Objectives

The technical panel suggested that, for the purpose of this project, the term “high RAP” should refer to mixtures having 30 percent RAP or more, and that the project should include development of high-RAP mixtures. The panel also recommended that this project would focus on the use of recycled pavement only, and not recycled shingles. This was due to concurrent national pooled-fund research investigating the use of tear-off shingles in asphalt mixes, and also MnDOT’s recently completed laboratory study on the use of manufactured and tear-off shingles in asphalt mixes.

Other objectives were that performance surveys should be conducted for in-service highway pavements having “traditional” levels of RAP. It was decided that county Pavement Management video logs be used to evaluate cracking. Project staff would use local road data to develop a matrix of in-service pavements based on Percentage of RAP, RAP Type, and Percentage New Asphalt Cement, and then report on “typical performance”.

As the project objectives were developed, it was noted that much of the latest research had been laboratory-based, and that one goal of this project was to continue the history of collaborative research between the asphalt industry and MnDOT. Industry, academic, or other collaborative asphalt mixture researchers would aid in fulfilling the laboratory and developmental research items.

With the help of the technical panel, the following objectives were developed for the project:

1. Determine the performance of local roadways built with typical RAP levels (less than 30 percent).
2. With the help of the asphalt industry, investigate the activation of RAP asphalt in a plant setting.
3. Based on objective #2, investigate the extent of RAP asphalt activation in a laboratory setting.
4. Develop high-RAP mixtures, and test them for low-temperature performance.
5. Present the results and recommendations in a final report.

Chapter 2. Sampling and Performance of RAP Sections in Minnesota

Research Approach

Minnesota county engineers were contacted in order to help identify highway pavements that: (1) were constructed using various percentages of Recycled Asphalt Pavement (RAP), and (2) had a performance history that could be accessed using the MnDOT Pavement Management network. The counties were asked to provide the following data:

- County Name
- Highway Number
- Project Limits
- Year Constructed
- Design Type (wear or non-wear)
- Mix Design Record
- Asphalt Performance Grade
- Total Percent Asphalt (recycled plus new)
- Percent RAP

The research staff followed up by accessing Minnesota's County Highway Testing Program to identify the applicable roadway segments, and then recorded the following pavement management data:

- County Name
- Highway Number
- Project Limits
- Survey Year
- Distance
- Transverse crack count
- Other observations

The pavement management data was sorted to determine typical performance according to the level of RAP present in asphalt mixtures.

Performance Matrix

Collaborating engineers from Olmsted, Pope, Wilkin, Itasca, and Dodge counties identified a number of projects and provided background data for the following matrix:

Table 1: Data Levels[a] for County RAP Performance

New Asphalt PG	Design AC %	New AC %	% RAP[b]	Age, Yrs	# Projects
58-28	4.8 – 6.3	3.0 – 6.3	0 – 40	1 – 11	22
52-34	5.2 – 6.1	3.0 – 6.1	0 – 40	3 – 11	39
58-34	5.5 – 6.2	4.3 – 6.2	0 – 20	1 – 5	6
64-28	6.2	6.2	0	8	1

(a) Mix design data. Results may change if using production data. (b) Includes 37 high-RAP data points.

Summary of Pavement Performance

County highway performance data was developed from a combination of video-log reviews and field inspections. The data was categorized by design asphalt Performance Grade, and averages were calculated for RAP content, design and add AC percentages, age, ratio of new to total AC, cracks per mile, and the spacing between cracks (as normalized by section length). The tabulated results are presented in Appendix A. A discussion of the data follows.

Performance Survey Results

Table 2 and Table 3 present average values from the performance survey and correlations between the various data categories.

Within the data set there was a high frequency of designs having 20 – 26 percent RAP. The bulk of survey data contained two asphalt binder categories; PG 52-34 and PG 58-28. It is interesting to note that among this group of county projects the greatest percentage of RAP use occurred in the PG 52-34 asphalt category. The fact that this category also showed a relatively short performance history of merely 1.8 years may indicate a new trend. The data contained 11 pavements that were constructed as overlaid bituminous surfaces, nine using PG 52-34 and two using PG 58-28. PG 52-34 overlays contained 30 percent RAP, and PG 58-28 overlays contained 30 or 40 percent RAP. The remaining pavements were either constructed on aggregate or reclaimed-type bases, or no information was provided.

Cracking analysis made no differentiation between bituminous pavements that were constructed as overlays versus those constructed on aggregate bases. Although this was a disadvantage to the PG 52-34 category, it had relatively better field performance compared to PG 58-28. In this case PG 52-34 showed a relative decrease of 40 percent in the number of cracks per mile and an improved crack spacing of 34 percent.

Table 2: Average Values from County Performance Survey by Design Asphalt Grade

AC grade	RAP	Total AC	Add AC	Age	New AC Ratio	Cracks per mile	Feet per Crack
58-28 (n=22)	20.0	5.5	4.5	6.7	81.2	87.2	148.4
52-34 (n=37)	26.8	5.4	4.2	1.8	76.5	62.3	225.8
52-34* (n=7)	11.4	5.7	5.2	3.9	90.8	34.6	163.0
58-34 (n=8)	20.0	5.6	4.5	3.5	79.4	1.6	1581.9
64-28 (n=1)	0.0	6.2	6.2	8.0	100.0	16.6	318.1
(*) Averages when pavements aged less than 1 year are excluded.							

A correlation matrix was used to explore the influence of variables on field performance. In the matrix, values near 0.0 reflect very weak relationships and values near -1.0 or 1.0 indicate strong relationships. The results, in Table 3: Part 1, show that the two cracking performance measures did not correlate well with the amount of RAP or other individual variables. At the best, weak relationships were obtained between Cracks per mile versus Age (0.214) and between AC-Grade versus Feet per crack (0.178). Because of the many low correlations, the PG 52-34 subset was reduced to only pavements that were greater than one year of age. The correlation was then re-calculated (in Part 2), and yielded stronger relationships. A strong relationship was found for Cracks per Mile versus Age (0.552), and mild relationships versus New AC Ratio (0.271) and percent RAP (-0.202). Mild-to-weak relationships were found for AC grade versus cracking performance, and weak relationships were found for the remaining variables.

Results indicate that performance was most affected by pavement age and the percentage of new AC in the mixture. Early performance of the sections did not entirely depend on the amount of RAP in the bituminous mixture. Two-sample student t-tests showed that none of the PG subsets were of equal age. PG 52-34 sections were especially affected by a relatively short performance history. It is expected that additional service life would further exploit any performance differences between RAP levels since several of the designs contained high (30 – 40 percent) amounts of RAP.

The nature of the selection process may have introduced bias into the data set. It is recommended that in any future studies this approach should be extended to a larger, randomly-selected, group to include pavement management and performance data, bituminous design record, and maintenance history if possible.

Table 3: Pearson Correlations for County Performance Data

Correlation Table Part 1: 62 of 77 cases						
	RAP	**AC grade**	**Total AC**	**Add AC**	**Age**	**New AC Ratio**
Cracks per mile	-0.088	0.011	0.106	0.106	0.214	0.106
Feet per crack	-0.054	0.178	0.027	0.002	-0.061	0.000
Correlation Table Part 2: 42 of 77 cases						
	RAP	**AC grade**	**Total AC**	**Add AC**	**Age**	**New AC Ratio**
Cracks per mile	-0.202	0.158	0.088	0.234	0.552	0.271
Feet per crack	-0.005	0.204	0.035	-0.065	-0.224	-0.054

Chapter 3. Activation of Recycled Asphalt in Plant and Laboratory Settings

This chapter summarizes plant monitoring and subsequent laboratory activities that were performed as part of a study on the activation of asphalt cement (AC), or binder, contained in Recycled Asphalt Pavement (RAP).

Research Approach

Research of RAP-asphalt activation was performed in two parts; first a plant study and then a laboratory study. Three blends of RAP and aggregates were heated in a batch plant without the addition of new liquid asphalt binder. After the RAP and aggregate product was evaluated for coating a series of laboratory iterations were performed in an attempt to mimic the outcome from the batch plant. Coating was evaluated using a modified AASHTO T195-67 (3) procedure.

AASHTO T195-67 (Modified)

AASHTO T195-67 is a procedure that is used to quantify the amount coating for mixtures of asphalt and aggregate. The procedure states:

- Sieve each material immediately, while it is still hot, on a 9.5-mm (3/8-in.) sieve for materials with a maximum size larger than 9.5 mm (3.8 in.). For materials with a maximum size of 9.5 mm (3.8 in.) or less, use a 4.75-mm (No. 4) sieve. Take a <u>sample large enough to yield between 200 and 500 coarse particles</u> retained on the 9.5 mm (3.8 in.) or 4.75-mm (No. 4) sieve. Do not overload the sieves. If necessary, sieve the sample in two or three operations. Shaking should be reduced to a minimum to prevent recoating of uncoated particles.
- Place the particles on a clean surface in a one-particle layer, and <u>start counting immediately</u>.
- Very carefully examine each particle under direct sunlight, fluorescent light, or similar light conditions. If even a tiny speck of uncoated stone is noted, classify the particle as “partially uncoated.” If completely coated, classify the particle as “completely coated.”

The activities of this project did not allow immediate evaluation of plant-mixed material. Therefore, AASHTO T195-67 was modified so that all plant and laboratory-mixed material would be evaluated under similar room temperature conditions.

Laboratory heating-activation iterations used materials that were obtained from stockpiles located at the batch plant. Because of limited quantities, laboratory batch sizes were generally between 2 and 2.5 kg (4.4 – 5.5 lb). The result was that half of the 26 laboratory batches contained less than 200 coarse particles; therefore the procedure was modified to allow samples having less than 200 coarse particles.

Plant Monitoring Activities

A plant-scale RAP activation experiment was performed in order to observe how asphalt is transferred from RAP to the virgin aggregate components of bituminous mixtures. The plant experiment consisted of blending different proportions of RAP with virgin aggregate at different temperatures and no additional liquid AC. Blending took place at the Crane Creek Asphalt Plant, shown in Figure 1, located in Faribault Minnesota. At the time of this experiment the plant was configured as a three tier batch mix plant equipped with six virgin aggregate belt-feed bins and one RAP belt feed bin. The mixing unit was a twin pugmill type with ≤ 0.75-in. clearance from the walls and timer controls for wet and dry mixing.

Figure 1: Crane Creek Batch Plant

RAP proportions were determined from two mixture designs to be used at the plant when commercial production commenced for the day. With this approach, large quantities could be produced, examined, and sampled, and the leftover material could be reheated and used at a project. Mix Design Record numbers 06-2009-138 and -141 were used. The RAP was sampled from millings that originated from a MnDOT construction project and blended with four types of virgin aggregates as shown in Table 4. The experiment used two RAP levels: 10 and 24 percent RAP.

Table 4: RAP and Virgin Aggregate Properties

Pit	Source of Material	TOTAL Sp. G	Minus #4	
			% Passing	Sp. G
66110	Nelson ¾” Rock	2.712	4	2.712
19123	Castle Rock ½” X #4	2.675	3	2.675
19123	Castle Rock Man Sand	2.627	100	2.627
66110	Nelson Man Sand	2.612	90	2.612
	TH 60 Millings	2.663	74	2.663

The virgin aggregate and RAP were blended in a single batch as shown in Figure 2. Various plant temperatures were measured at the point of discharge with integrated plant sensors. The temperature and RAP content for all iterations are shown in Table 5. Temperatures were also measured at the point of sampling using a handheld thermometer.

Figure 2: Crane Creek Batch Size

Table 5: Blending Iterations

Run No.	Plant Temp (°F)	RAP Content (%)	Dwell Time (Sec.)	Sample Temp. (°F)
1	420	10	30	320 (Front) - 344 (Back)
2	490	24	30	290 – 300
3 (1st half)	400	24	30	230 (Front)
3 (2nd half)	375	24	30	225 (Back)

Plant Activation Observations

- Recycled binder clumped around fines and formed 'balls'
- RAP binder appeared to activate in all iterations
- Higher concentrations of RAP yielded noticeably more binder activation
- Higher temperatures yielded greater activation (blending) of the recycled binder
- Iterations from the plant experiment were evaluated in the laboratory using AASHTO T195-67 (modified). Results from the plant experiment are shown later in the report along with results from the laboratory RAP activation experiment.

Figure 3: Plant Activation Run No. 1

Figure 4: Plant Activation Run No. 2

Figure 5: Plant Activation Run No. 3

Samples

Samples were retained for laboratory evaluation and for use in additional activation studies.

- Three 5-gallon samples of each iteration (run no.)
- Two 5-gallon samples of virgin aggregate material (Castle Rock + Nelson Sand)
- One 5-gallon pail of Nelson ¾" Rock
- Two 5-gallon pails of RAP material (TH 60 Millings)
- Two sealed plastic bags of RAP material (TH 60 Millings)
- One sealed plastic bag of crushed BMI millings (Not used in the mixing experiment)

Laboratory RAP Activation

A set of aggregate blends were produced. The blends and a corresponding amount of RAP material were oven heated separately at assigned temperatures and times, and then mixed for an assigned length of time. The RAP-aggregate mixtures were allowed to cool to room temperature and then asphalt coating was evaluated using AASHTO T 195-67 (modified). Results from the

Laboratory Activation coating evaluation were compared to results from RAP-aggregate mixtures produced during the Plant Experiment. Most of the iterations contained a small quantity of material – approximately 2,500 grams, so a bucket mixer (Figure 6) was used. Four of the iterations contained 15,000 grams of material, an amount typical of laboratory trial-mix batches, so were blended using a paddle mixer suited for bituminous laboratory production work (Figure 7).

Figure 6: Bucket Mixer and Agitator

Figure 7: Bituminous Design Mixer

Materials and Blends

Materials collected during the Plant Experiment were divided and proportioned so that 14 iterations were possible at a RAP content of 23 percent, 10 were possible at a RAP content of 10 percent, one was possible at a RAP content of 50 percent, and one iteration was possible at 100 percent.

Temperature and Mixing Time Parameters

Laboratory heating temperatures were selected according to practical operating range of ovens. High laboratory temperature was set at 320 °F (160 °C). Normal laboratory heating temperature was set at 290 °F (143 °C), and mixing temperatures varied between 72°F (22 °C) and 320°F (160 °C). Normal mixing time was set at 10 minutes according to MnDOT Trial Mix Lab practice, and normal heating time was set at 3 hours. Heating time varied from 0 to 180 minutes and mixing time varied between 30 seconds and 10 minutes.

Observations and Data Analysis

Figure 8 to Figure 10 provides a visual comparison of the effect of plant versus laboratory production and the percent RAP on the aggregate blend. Figure 8 is a photo taken at the plant. Occasional clumping was present in each stockpile, but was not present in these random samples. One field observation was that plant mixing time and temperature affect the activation of RAP.

Figure 8: Plant Activation Trials No. 1, 2, and 3 (Left to Right)

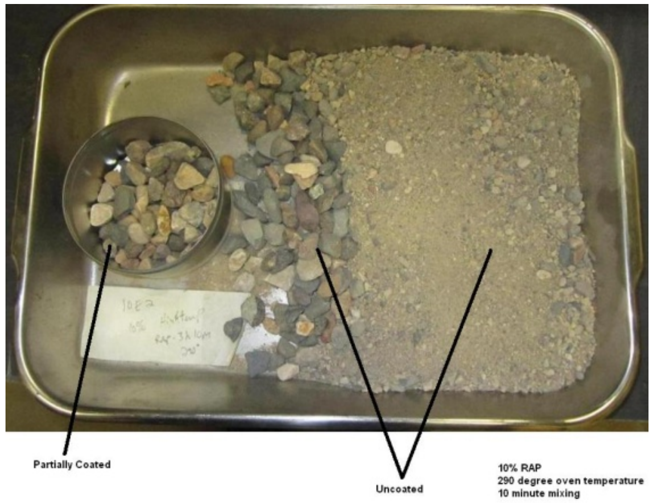


Figure 9: Example of 2,500 gram Lab Activation Trial at 10% RAP

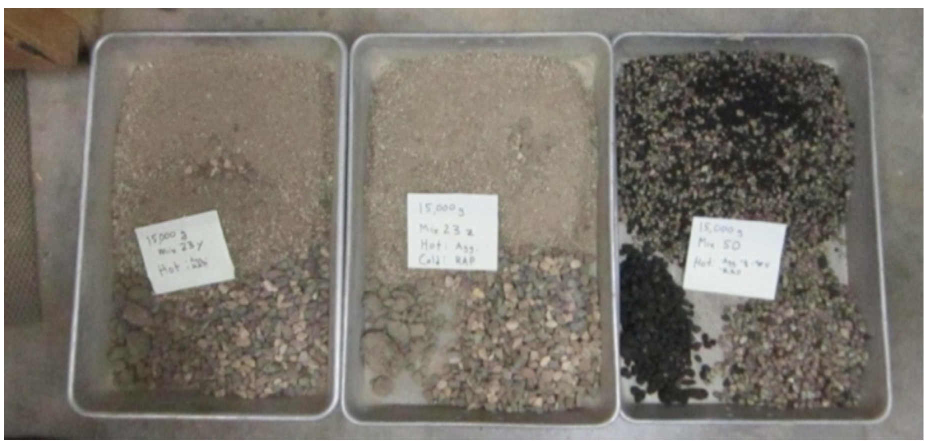


Figure 10: Examples of 15,000 gram Lab Activation Trials at 23 and 50% RAP

The results of AASHTO T195-67 (modified) evaluations are presented in Figure 11. Batch codes along the horizontal axis, such as Batch23A2, describe the laboratory iteration. In this case the number 23 represents the RAP content, the letter A represents the set of heating conditions (found in Appendix B), and the final number 2 gives the test replicate number.

Figure 11 shows a large percentage of uncoated particles were found in nearly all batches. In cases resulting in no uncoated particles (good coating), either the laboratory RAP content was above 50 percent, or the batches were produced by plant mixing.

The figure also shows that 10 percent RAP batches achieved partial coating levels near 20 percent, but produced nearly zero percent fully coated aggregates.

A coating comparison for the mixing methods in small bucket-mixer batches (Batch23A – E) versus large laboratory-mixer batches (Batch23Z) showed that for these materials there was relatively little difference regarding complete, partial, and uncoated percentages.

Figure 11: Asphalt Coating AASHTO T195-67 (modified)

It was not possible to duplicate the influence of plant mixing in the laboratory. Plant mixed aggregates achieved a more uniform coating than those that were laboratory mixed. Partially coated laboratory mixed aggregates typically showed abrasion with little observed transfer of asphalt material. Observations indicated that asphalt was pulverized and was incorporated into the aggregate fraction passing the #4 (4.75-mm) sieve; sizes not evaluated by AASHTO T195-67 (modified).

Although it was not possible to duplicate the plant mixing in a laboratory, it was possible to observe there were differences between the laboratory produced iterations. Three predictive models were fitted in order to learn about the effect of various parameters on the level of coating.

RAP Transfer Modeling

In order to further investigate the relative effect of test parameters, multiple-linear-regression (4) was performed on the set of data results obtained from laboratory simulation of batch-plant RAP activation. Three regressions addressed the possible coating outcomes (complete, partial, and none) as a function of Total Aggregate > 3/8-in., Temperature of aggregates, Percent RAP, Mixing time, and Heating time of RAP.

Table 6: Summary of Regression Results using ARC

Parameter	Model Name		
	Complete Coating	***Partial Coating***	***No Coating***
Total Aggregate > 3/8-in. *(P-values)*	*0.0000*	*0.0000*	*0.0652*
Temperature of Aggregates *(P-values)*	*0.3437*	*0.0119*	*0.0196*
% RAP *(P-values)*	*0.0000*	*0.8918*	*0.0000*
Mixing Time *(P-values)*	*0.5444*	*0.0890*	*0.1154*
Heating Time of RAP *(P-values)*	*0.3875*	*0.0800*	*0.1423*
Model F-Value	283.7	103.71	24.59
Model R-Squared	0.986	0.963	0.860

Complete results for each model are included in Appendix B. P-values in Table 6 indicate the likelihood that the parameter should occur in the model. Combinations of large R-squared and F-value factors indicate that the response is explained well by the model. Low R-squared and F-value factors indicate there is a need to revise the model, perhaps by including additional factors that explain the response. In this case the No Coating model fit was relatively poor, and the Complete Coating model was relatively good.

In the case of this data set, the analysis identified the parameters of Temperature, Mixing Time, and Heating Time of RAP as being the most influential for complete coating in laboratory mixing situations. This supports the observations made in the field during the Plant Activation phase. The %RAP parameter was also important in explaining the amount of partial coating, an effect that is undetectable during a Plant Activation study or in any scenario where liquid asphalt is added to the blend.

Chapter 4. High RAP Mixtures Designs

The focal point of this chapter was the development of a testing matrix for low-temperature performance testing. The matrix was developed by project staff at MnDOT and the University of Minnesota. Initial designs were developed by MnDOT, who then provided the designs and materials to the University of Minnesota for the mixing and testing phase.

Materials for Mixture Development

A number of aggregates were selected for mixture design based on the criteria of suitability as bituminous aggregate and their use in previous research projects. Use in previous research was an important consideration since it allows potential comparisons of results from different test methods for a wide range of recycle content. The aggregates were different from the set described in Chapter 3.

A baseline Job Mix Formula was selected. The formula had been used in commercial bituminous mixture production for over 5 years, and was the same design as the control mixture used for prior asphalt-shingle research in MnDOT's report published in 2010 (2). The mixture met requirements for a MnDOT Superpave 12.5 nominal maximum aggregate size, traffic level 3 (1-3 million ESAL's). The basic design blend was later adjusted in the laboratory by varying the amounts of RAP in the study matrix. Similar aggregate gradations were targeted each mixture, so virgin aggregate component percentages varied according to recycle content. Each mix was adjusted to target mixture design requirements of: 4.0 voids, minimum 14.0 VMA, 65-78 VFA, and a Dust to Binder ratio of 0.6-1.2. Film thickness criteria were not used for design.

The aggregate structure of the various mixtures consisted of a pit run sand, a quarried 0.75-in. dolostone, quarried dolostone man sand, and a 0.75-in. RAP. See Table 7 for a description of the aggregate products.

Table 7: Aggregate Products

Sieve	% Passing by Weight				
	Pit Sand	**Crushed Rock**	**Manufactured Sand**	**BA ¾**	**RAP**
3/4	100	100	100	100	100
1/2	100	60	100	90	94
3/8	99	37	100	83	87
#4	97	3	99	70	69
#8	90	1	75	61	55
#16	78	1	48	45	44
#30	54	1	33	34	32
#50	27	1	19	28	18
#100	7	1	6	13	10
#200	3	1	3	3.8	6.6
%AC					
	0	0	0	0	5.6
Bulk Specific Gravity					
Gsb	2.662	2.707	2.709		2.626
-#4 Gsb	2.662	2.707	2.709		2.626

The mix designs were considered to be fine graded. Materials were selected so that all of the mixtures had single faced crushing of at least 55 percent and Fine Aggregate Angularity of 42. Two asphalt binders were selected for this project, a Flint Hills PG 58-28 and a PG 58-34.

Prior to batching and mixing, the virgin aggregate products were split into coarse and fine fractions on the #8 sieve. The plus #8 material was processed further by separating into individual size fractions from the 0.75-in. through the #8. The RAP was split on the #4 sieve and the plus #4 material was processed further by separating into individual size fractions from the 0.75-in. through the #4. The aggregate fractions were later recombined into the proper proportions during mixture blending. The batching weight of the RAP was adjusted for its binder content.

Mixture Development

Issues

Asphalt mixture designers face the challenge of competitively producing cost-effective mixtures that also satisfy the minimum requirements set forth in construction specifications. Low-temperature performance is a major issue with owner-agencies. Among other things, the percentage of recycled materials and their material properties can influence the success of a pavement design. This test matrix was developed to include high and low recycle percentages while attempting to enhance low temperature performance with the use of softer asphalt binder.

MnDOT construction standards are often used by counties and cities in Minnesota, so a set of bituminous mixtures was developed based on MnDOT specifications for RAP use in bituminous surfaces. The MnDOT standard specifications for construction (1) include the current standards and guidelines on the use of RAP. The gyratory design specification requires that the composite RAP and virgin aggregates meet the composite fine aggregate angularity for the mixture being produced, as well as the appropriate aggregated quality tests.

Although the current specification places no limitation on the amount of RAP allowed in the mixture, the maximum allowable recycled asphalt binder content is governed by criteria for the percent of virgin asphalt binder relative to the total binder content (New AC/Total AC). In 2011 this requirement was established as 70 percent as a measure to increase durability and performance. In 2013 the MnDOT criteria was revised to 65, 70, and 80 percent for certain mixtures in accordance with Table 8. It applied to all mixtures using any combination of RAP and recycled asphalt shingles (RAS). MnDOT's maximum allowed amount of RAS is 5 percent by weight. When the maximum amount of RAS is used this generally restricts the amount of RAP to 10 percent (2).

Table 8: MnDOT Minimum Ratio of Added New Asphalt Binder to Total Asphalt Binder (%)

Requirements for Ratio of Added New Asphalt Binder to Total Asphalt Binder min%:			
Specified Asphalt Grade	**Recycled Material**		
	RAS Only	**RAS + RAP**	**RAP Only**
PG XX-28, PG 52-34, PG 49-34, PG 64-22,			
Wear	70	70	70
Non-Wear	70	70	65
PG 58-34, PG 64-34, PG 70-34			
Wear & Non-Wear	80	80	80

Table 9 illustrates examples of theoretical binder ratios that are possible for bituminous designs having 6 percent total asphalt binder (Pb) and RAP containing between 3 and 5 percent recycled asphalt cement (AC). Under these parameters, and with MnDOT limitations, the contribution of recycled asphalt cement binder (Pb_R) to the entire mixture is 1.8 percent. The designs in Table 9 meeting the current New AC/Total AC percent criteria would be allowed as long as the design satisfies all other requirements of the mixture specifications.

Table 9: Binder Ratio Example

RAP Proportion	Virgin Aggregate Proportion	AC Content of RAP	Design Pb	Pb_R	Pb_V	Pb_V /Pb
0	100	3	6	0	6	100
25	75	3	6	0.75	5.25	87.5
40	60	3	6	1.2	4.8	80
55	45	3	6	1.65	4.35	72.5
60	40	3	6	1.8	4.2	70
0	100	4	6	0	6	100
25	75	4	6	1	5	83.3
40	60	4	6	1.6	4.4	73.3
45	55	4	6	1.8	4.2	70
55	45	4	6	2.2	3.8	63.3
0	100	5	6	0	6	100
25	75	5	6	1.25	4.75	79.2
36	64	5	6	1.8	4.2	70
40	60	5	6	2	4	66.7
55	45	5	6	2.75	3.25	54.2

Test Matrix

RAP quality is dependent on the aggregate and the binder components as well as the age of pavement. If a particular RAP source is comprised of a satisfactory recycled aggregate component, the remaining concern would be the quantity and material properties of the recycled binder.

A wide variety of bituminous mix designs exist for many different surfacing applications. Those designs may contain asphalt cement (AC) levels presumed to fall between 4 percent on the very dry end, and 7 percent on the very rich end. The potential RAP components of those designs may conservatively contain 3 to 5 percent AC. MnDOT mixture specifications require that designs satisfy volumetric, percent new binder, and binder and aggregate material requirements. For agencies specifying a 70 percent new binder ratio design criterion it is theoretically possible that dry bituminous designs using 4 percent asphalt could allow between 24 to 40 (32 average) percent RAP, and rich designs using 7 percent asphalt could allow between 42 to 70 (56 average) percent RAP if all other requirements were satisfied (Figure 12).

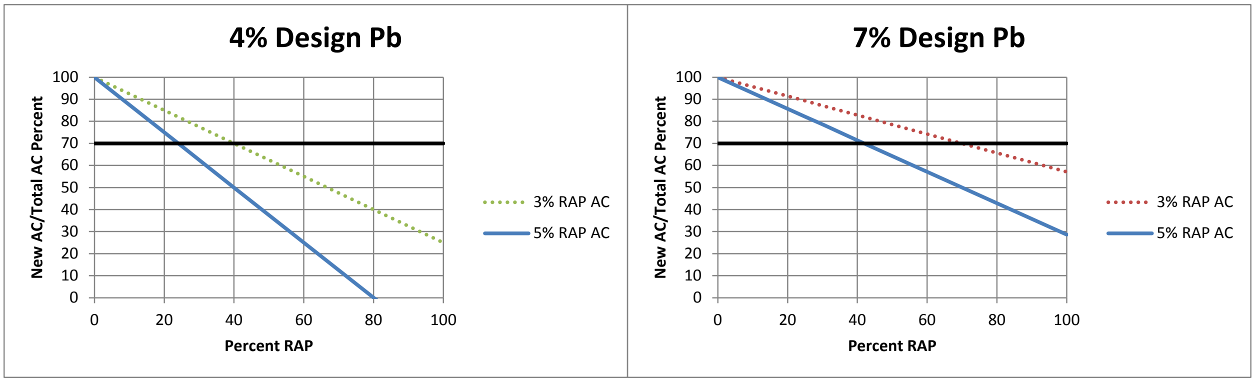


Figure 12: Theoretical New/Total Asphalt Ratios

The test matrix (Table 10) was composed of eight asphalt mixtures. The matrix included designs that would contain four RAP levels, with the maximum near the theoretical maximum percentage possible when using a 70 percent new binder ratio.

It has been found that PG 58-28 is the most frequently used binder grade in Minnesota and that mixtures containing low PG-34 asphalt binder show favorable early field performance (5). The matrix therefore included the use of the two asphalt binders to compare the effect of virgin asphalt low PG grade on the low temperature laboratory performance of high RAP mixtures.

Table 10: High-RAP Mixture Test Matrix

Mix	Recycle Content	Binder PG
1	RAP 0%	58-28
2	RAP 0%	58-34
3	RAP 25%	58-28
4	RAP 25%	58-34
5	RAP 40%	58-28
6	RAP 40%	58-34
7	RAP 55%	58-28
8	RAP 55%	58-34

Mixture Designs

Four preliminary mixture designs were produced for the eight mixtures in the laboratory evaluation phase of the project. The RAP contents of the designs were such that the New/Total AC ratios for two designs were greater than 70 percent and two were less than 70 percent (Table 11 and Table 12). For this particular RAP material, containing 5.6 percent AC, the 70 percent criterion would theoretically limit the use of RAP to 28 percent.

Design worksheets for the preliminary designs are shown in Appendix C. The worksheets include:

- Design Sheets that were used to produce trial gradations and asphalt percentages using individual product gradation data, target void content, and target VMA. The resulting designs were charted on the Gradation Plot.

- Gradation Plots show the trial aggregate mixture blends produced on the Design Sheet.
- Batching Sheets show materials quantity requirements. The Batching Sheets in Appendix C can be used for producing laboratory mixtures of 10,000, or alternatively 15,000 grams.

Table 11: Asphalt Percentages

Mix Type	Design AC Percent	RAP AC Percent	New AC Percent	New/Total AC Ratio
RAP 0%	5.4	0	5.4	100
RAP 25%	5.4	1.4	4.0	74
RAP 40%	5.4	2.2	3.2	59
RAP 55%	5.4	3.1	2.3	43

Table 12: Mixture Proportions and Specific Gravities

Pit sand %	Crush rock %	Man sand %	RAP %	Mix Gsb
37	25	38	0	2.691
30	25	20	25	2.673
20	20	20	40	2.665
15	15	15	55	2.656

Chapter 5. Low-Temperature Testing of Asphalt Mixtures

Introduction

One major concern with applying high amounts of RAP in HMA mixtures is the effect on low temperature properties. During this phase of low temperature testing, Indirect Tension and Semi-Circular Bend (IDT and SCB) tests of asphalt mixtures were performed by the University of Minnesota Civil Engineering Department. The goal of this phase of mixture testing was to compare the effects of increasing RAP content as measured by low-temperature laboratory test procedures.

Test Description

Three different test methods, IDT creep, IDT strength and SCB fracture test, were performed to obtain creep, strength, fracture energy, and toughness of each asphalt mixture.

The IDT test method is performed on circular specimens cut from 150-mm (6-in.) diameter, gyratory compacted pucks or field cores. The specimens are loaded in diametral compression. Creep compliance; a function of strain, stress, and time, may be compared with strength as in indication of low temperature performance.

SCB testing uses a variation of three-point bending on D-shaped, 150-mm (6-in.) diameter, specimens. The specimens are produced from discs cut from gyratory-compacted pucks or field cores. A notch in the flat side of the "D" gives a path for tensile cracking. The specimen is loaded on the curved face. Research on Minnesota mixtures has been used to show that SCB test outputs of fracture toughness and fracture energy differentiate the low-temperature performance of asphalt mixtures (6). Marasteanu et al (6) also found that the peak in mixture fracture toughness was related to asphalt binder PG critical temperature.

Testing protocol for IDT and SCB testing called for two different temperatures. These were based on the binder low temperature performance grade: the first was at PG (-28ºC for 58-28 mixture and -34ºC for 58-34 mixture), and the second at PG + 10ºC (-18ºC for 58-28 mixture and -24ºC for 58-34 mixture). At each temperature, three replicates were tested for each mixture testing set (IDT creep, IDT strength and SCB fracture test). Additional detailed information about the test methods may be found in the referenced document (7).

Test Specimens

Eight sets of gyratory compacted specimens with four different levels of RAP (0, 25, 40, and 55 percent) were produced using the materials and designs provided by MnDOT. Two different types of binder, PG 58-28 and PG 58-34, were used in this work. Table 13 and Table 14 provide a description of the mixtures.

Table 13: High RAP Mixtures in Low Temperature Experiment

	Mix ID	Binder PG
1	RAP 0%	58-28
2	RAP 0%	58-34
3	RAP 25%	58-28
4	RAP 25%	58-34
5	RAP 40%	58-28
6	RAP 40%	58-34
7	RAP 55%	58-28
8	RAP 55%	58-34

Table 14: Properties of Test Specimens with 0 to 55% RAP

Mix ID	Binder PG	Puck #	G_{mm}	G_{mb}	Air void (%)[a]	Adj. Asphalt Film Thickness, avg. μ
RAP 0%	58-28	1	2.514	2.338	7.0	8.5
		2		2.341	6.9	
		3		2.344	6.8	
	58-34	1	2.517	2.342	7.0	8.4[b]
		2		2.342	7.0	
		3		2.334	7.2	
RAP 25%	58-28	1	2.501	2.332	6.8	9.0
		2		2.340	6.4	
		3		2.338	6.5	
	58-34	1	2.503	2.337	6.7	8.8
		2		2.325	7.1	
		3		2.342	6.4	
RAP 40%	58-28	1	2.508	2.344	6.5	8.1[b]
		2		2.340	6.7	
		3		2.335	6.9	
	58-34	1	2.502	2.336	6.7	8.3[b]
		2		2.338	6.7	
		3		2.340	6.6	
RAP 55%	58-28	1	2.510	2.339	6.8	7.6[b]
		2		2.341	6.7	
		3		2.335	7.0	
	58-34	1	2.507	2.338	6.7	7.6[b]
		2		2.340	6.7	
		3		2.336	6.8	
(a) Average voids of 6.8% with standard deviation of 0.2%. (b) Below MnDOT's current standard of 8.5 μ						

Low Temperature Testing and Data Analysis

IDT Creep Test

IDT creep tests were performed for 1000 second loading time. The inverse of creep compliance, creep stiffness *S(t)*, was calculated at 60 second and 500 second loading times, and the values were used in the data analysis. Table 15 summarizes the average creep stiffness values at 60 and 500 seconds, *S(60s)* and *S(500s)*, for all mixtures tested. The coefficient of variation is reported along with *S(60s)* and *S(500s)*.

Table 15: Summary of IDT Creep Test

Binder PG	RAP, %	Test Temperature, ºC	Creep Stiffness			
			S(60s), GPa	C.V., %	S(500s), GPa	C.V., %
58-28	0	-18ºC	14.116	12.8	9.768	7.0
	25		16.584	20.6	11.641	11.7
	40		18.042	4.2	13.877	5.4
	55		19.109	6.0	14.828	8.8
	0	-28ºC	20.700	12.4	16.431	11.7
	25		19.544	7.7	16.308	8.0
	40		25.364	15.8	20.561	12.8
	55		25.525	7.1	21.030	4.8
58-34	0	-24ºC	13.986	16.8	9.478	12.4
	25		16.707	8.9	12.065	1.7
	40		19.697	23.2	15.136	21.7
	55		19.705	8.5	16.081	9.1
	0	-34ºC	23.084	20.6	19.278	15.7
	25		23.597	10.5	19.597	4.2
	40		22.602	13.3	20.030	11.5
	55		28.447	7.8	23.665	7.4

The average values are also plotted in Figure 13 and Figure 14.

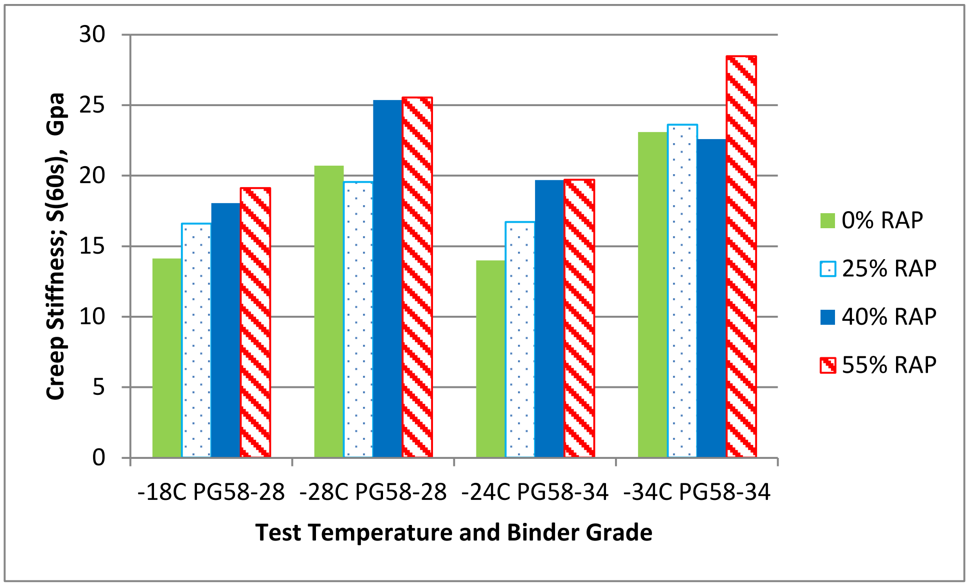


Figure 13: Comparison of Creep Stiffness at 60 Seconds, S(60s)

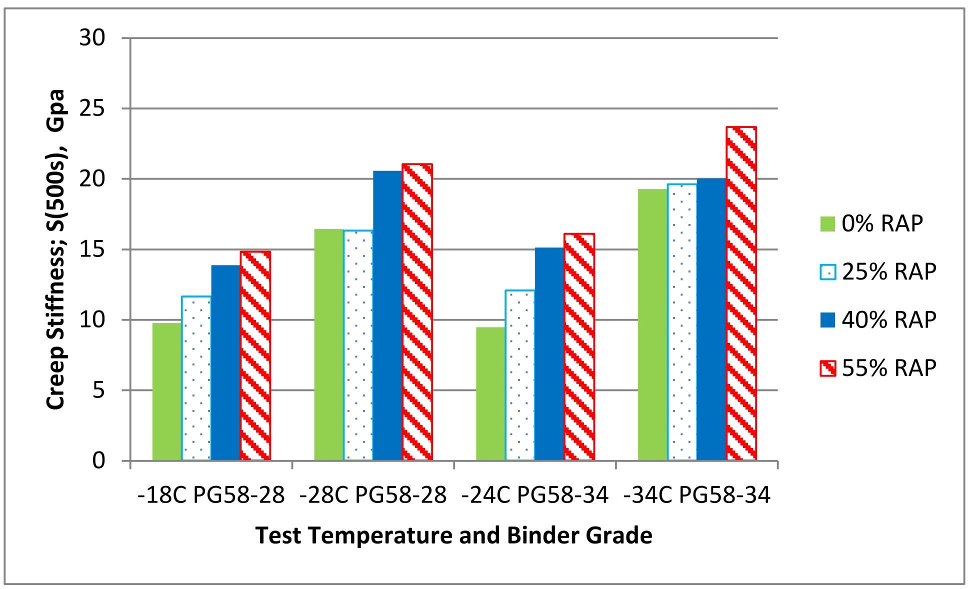


Figure 14: Comparison of Creep Stiffness at 500 Seconds, S(500s)

It can be observed that at PG + 10ºC the mixtures are ranked in the order of the RAP content: the higher the content the higher the stiffness at both 60s and 500s. At PG temperature, the differences between mixtures diminished; however, the mixture with 55 percent RAP still had the highest values at both 60s and 500s.

Creep stiffness and temperature were sorted by PG group and plotted in the following charts. Figure 15 shows PG 58-34 produced a benefit, by decreasing low temperature stiffness, when no RAP was used.

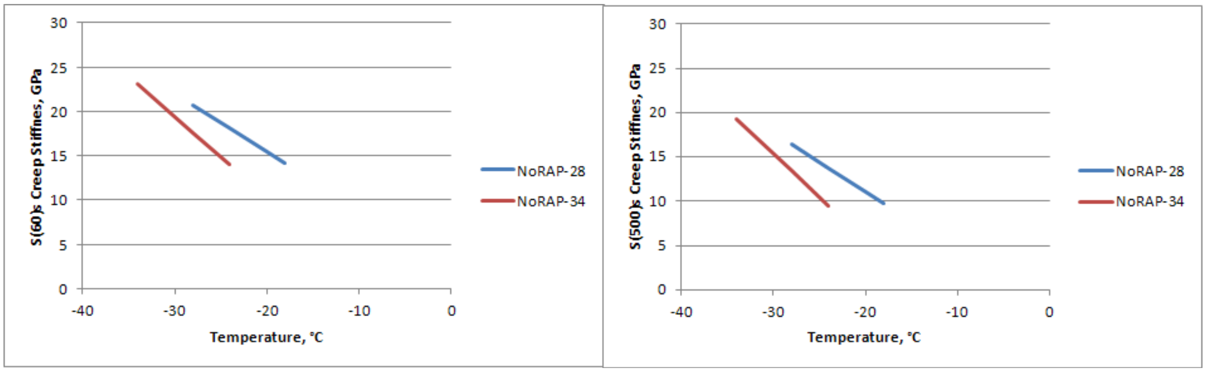


Figure 15: Creep Stiffness at 0% RAP: Low PG-28 and Low PG-34

Figure 16 shows the PG 58-34 benefit to low temperature stiffness was still present, but diminished when 25 percent RAP was used.

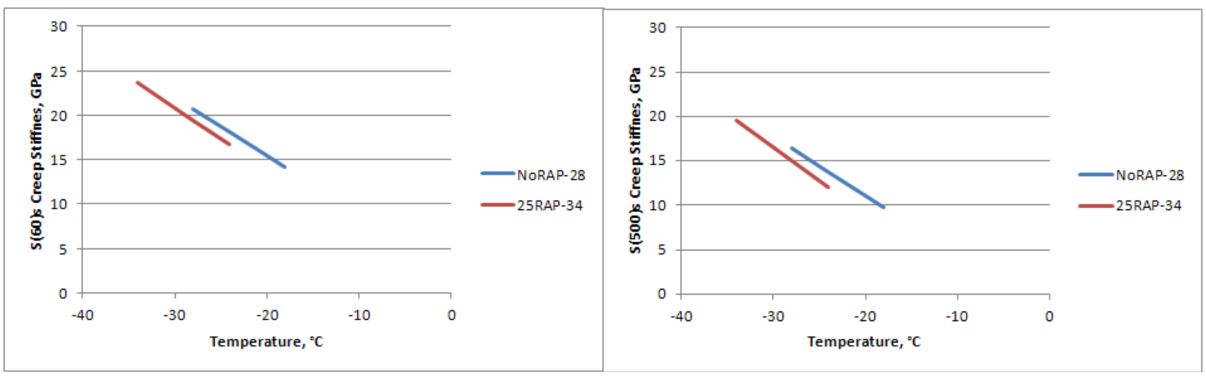


Figure 16: Creep Stiffness at 0% versus 25% RAP: Low PG-28 and Low PG-34

Figure 17 shows PG 58-34 added no benefit to low temperature stiffness when 40 percent RAP was used. The trend of increased stiffness continued in the case of 55 percent RAP.

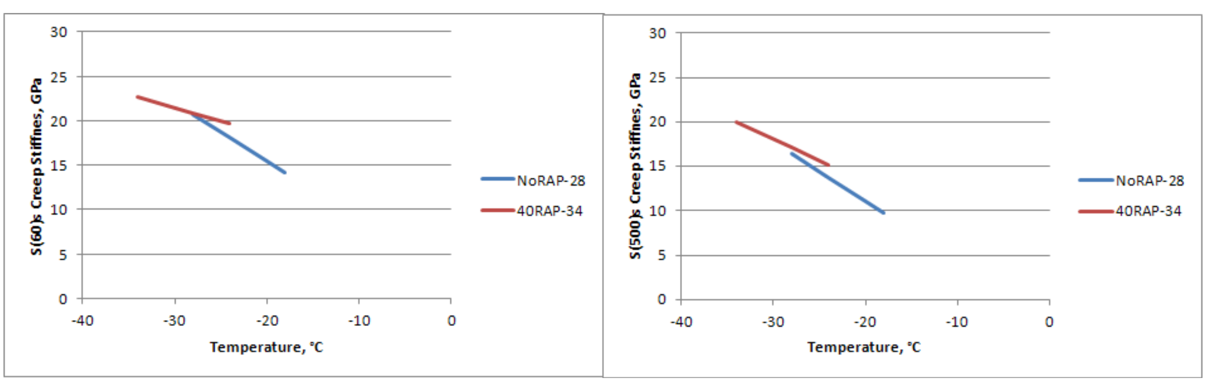


Figure 17: Creep Stiffness at 0% versus 40% RAP: Low PG-28 and Low PG-34

A comparison exclusively within the PG 58-28 IDT set produced a similar trend, as expected.

IDT Strength Test

Similar to IDT creep test, strength properties of asphalt mixture were investigated at two test temperatures: PG and PG + 10ºC. A summary of IDT strength values is given in Table 16 and the average values are also plotted in Figure 18.

It can be observed that in most cases, the RAP mixtures had slightly higher strength values than the control mixture, except for the results obtained for the 58-34 binder mixtures tested at PG temperature, for which the control was stronger than the RAP mixtures. In the following section it is shown that, for these test conditions, the slight increases in IDT strengths (with higher-RAP mixtures) were not sufficient to offset much larger increases in thermal stress.

Table 16: Summary of IDT Strength Tests

Binder PG	RAP, %	Test Temp, ºC	IDT strength	
			σ, MPa	C.V., %
58-28	0	-18ºC	3.410	3.4
	25		3.540	4.1
	40		3.679	7.3
	55		3.622	7.4
	0	-28ºC	2.534	16.8
	25		2.843	3.4
	40		3.044	7.0
	55		3.329	8.6
58-34	0	-24ºC	3.691	7.8
	25		3.504	2.9
	40		3.988	2.4
	55		4.142	0.4
	0	-34ºC	3.389	6.1
	25		3.040	19.5
	40		3.123	15.6
	55		3.301	9.2

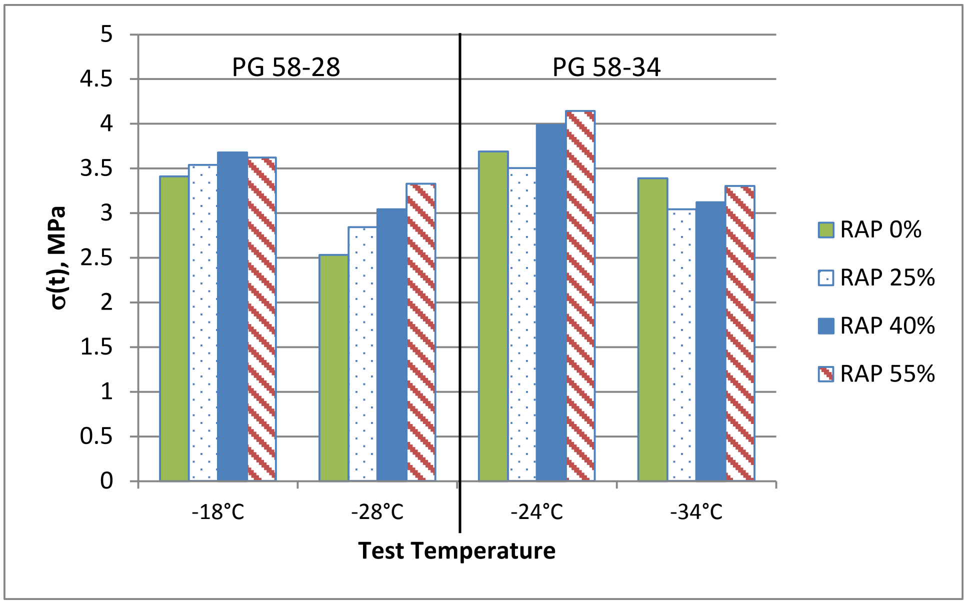


Figure 18: Comparison of IDT Strength

Critical Cracking Temperature (T_{CR}) from IDT Testing

The critical cracking temperature, T_{CR}, was computed from IDT creep and strength results. Thermal stresses were calculated from IDT creep testing assuming two different asphalt binder cooling rates: 1ºC/hour and 10ºC/hour. T_{CR} was obtained as the point of intersection of thermal stress and IDT strength master curve. Detailed information about thermal stress calculations can be found in the referenced document (8). The results are presented in Table 17 and Figure 19 to Figure 22.

Table 17: Summary of Calculated T_{CR}

Binder PG	RAP, %	T_{CR}, ºC	
		1ºC/hour	10ºC/hour
58-28	0	-22.2	-18.9
	25	N/A	N/A
	40	N/A	N/A
	55	N/A	N/A
58-34	0	-33.6	-29.6
	25	-24.7	N/A
	40	-24.0	N/A
	55	N/A	N/A

N/A: thermal stress and strength curves did not intersect

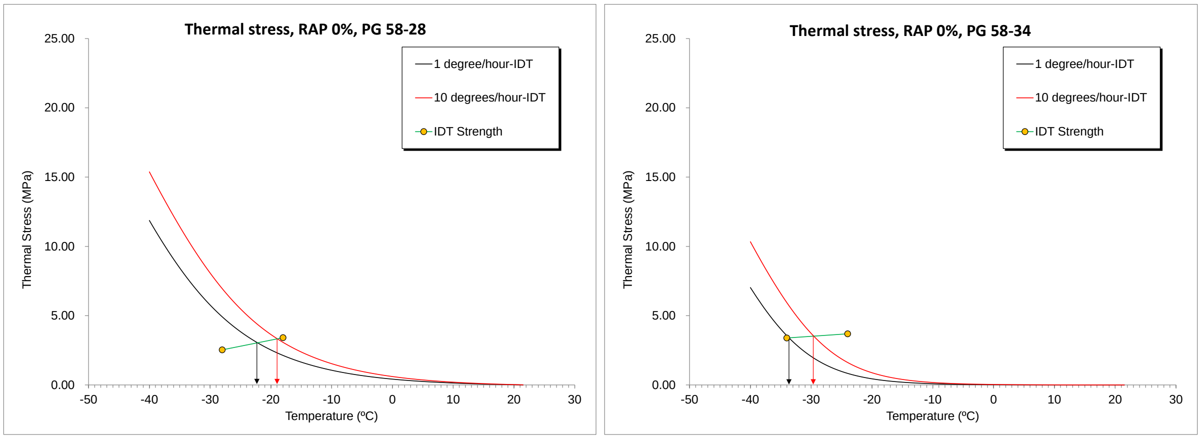


Figure 19: TCR from RAP 0% Mixtures (for PG 58-28 and 58-34 Binders)

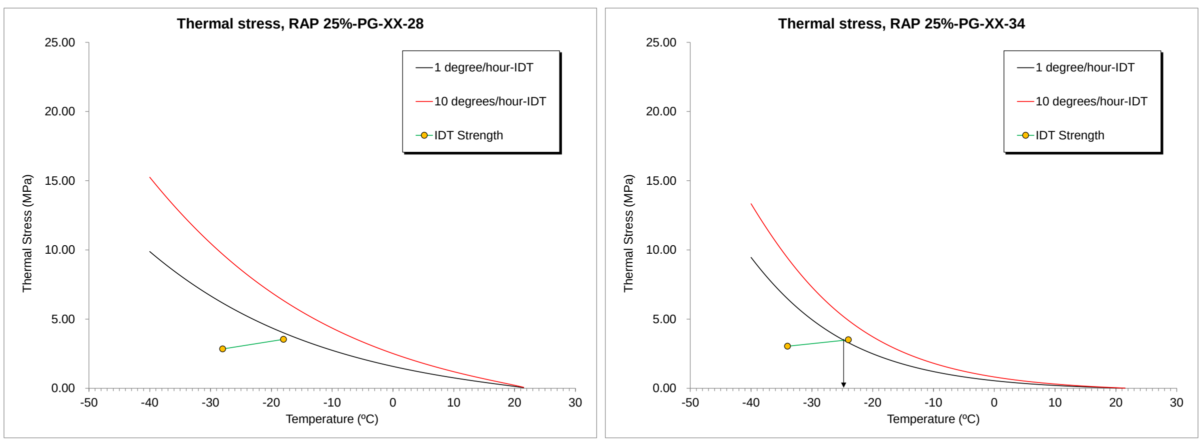


Figure 20: TCR from RAP 25% Mixtures (for PG 58-28 and 58-34 Binders)

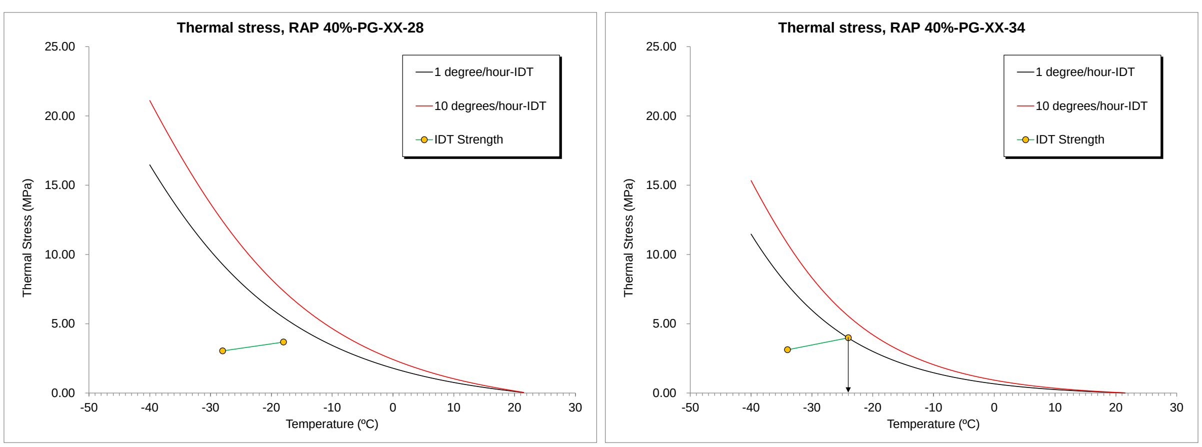


Figure 21: TCR from RAP 40% Mixtures (for PG 58-28 and 58-34 Binders)

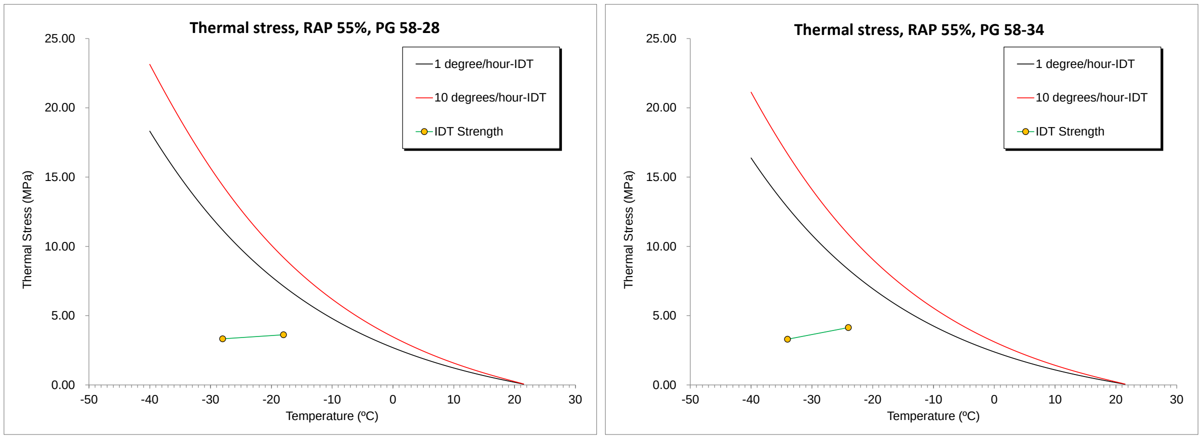


Figure 22: TCR from RAP 55% Mixtures (for PG 58-28 and 58-34 Binders)

From the limited Tcr data, it was observed that the control mixture (0 percent RAP) with the PG 58-34 binder had a critical temperature lower by more than 10 ºC than the mixture with the PG 58-28 binder; -33.6 versus -22.2 °C, or -29.6 versus -18.9 °C. It can be also seen that the addition of RAP increased the critical temperature for the PG 58-34 binder. This method produced similar Tcr values for the control PG 58-28 and the 25 percent-RAP PG 58-34 mixtures at the 1°C/hour cooling rate.

Data was limited due to non-intersection of strength and stress values. Strengths were much lower than the thermal stress values due to the increase in stiffness and reduction in relaxation with the addition of RAP.

SCB Fracture Test

Two fracture properties, fracture toughness, K_{IC} (MPa*m$^{0.5}$), and fracture energy, G_f (KJ/m^2), were calculated and compared. The fracture energy, G_f, is calculated as the area beneath a load versus load line displacement *P-u* plot. Figure 23 is an example of such a plot containing six curves produced using six specimens and two different temperatures. Detailed information about the calculation process can be found in referenced documents (8, 9). Prior research (10) suggests that, for SCB fracture toughness and fracture energy at PG + 10°C conditions, the respective minimum values of 0.8 MPa*m$^{0.5}$ and 0.35 KJ/m2 are recommended to inhibit thermal cracking.

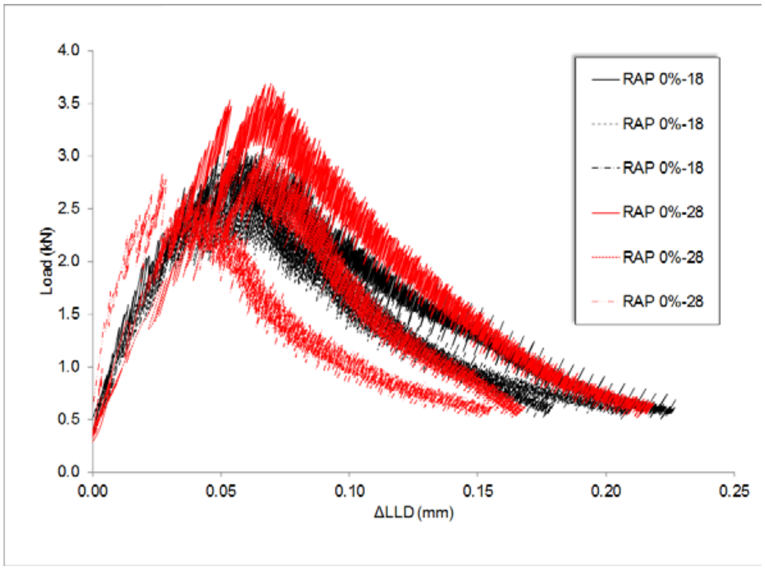


Figure 23: Example of P-u plot (0% RAP Mixture with PG 58-28)

Summary table and plots of K_{IC} and G_f are shown in Table 18, and Figure 24 and Figure 25, respectively.

As expected, the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, in particular at the lowest test temperature of PG. For most cases, the highest RAP content appeared to be the most detrimental to fracture properties, particularly for the lowest temperature.

Table 18: Summary of Mixture SCB Fracture Toughness and Fracture Energy

Virgin Binder Component	RAP, %	Temp, ºC	Fracture Toughness		Fracture Energy	
			K_{IC}, $MPa*m^{0.5}$	C.V., %	G_f, KJ/m^2	C.V., %
58-28	0	-18ºC	0.637	7.9	0.218	12.6
	25		0.646	2.5	0.188	28.5
	40		0.689	12.6	0.213	13.2
	55		0.740	6.6	0.208	18.1
	0	-28ºC	0.693	13.5	0.210	32.1
	25		0.732	2.1	0.169	8.1
	40		0.736	7.5	0.198	14.8
	55		0.673	3.7	0.157	10.6
58-34	0	-24ºC	0.761	9.3	0.268	10.2
	25		0.690	6.6	0.206	11.5
	40		0.727	8.4	0.211	7.0
	55		0.791	9.2	0.234	16.3
	0	-34ºC	0.767	4.2	0.244	5.5
	25		0.774	6.3	0.217	10.9
	40		0.895	3.8	0.204	14.7
	55		0.801	9.7	0.185	35.5

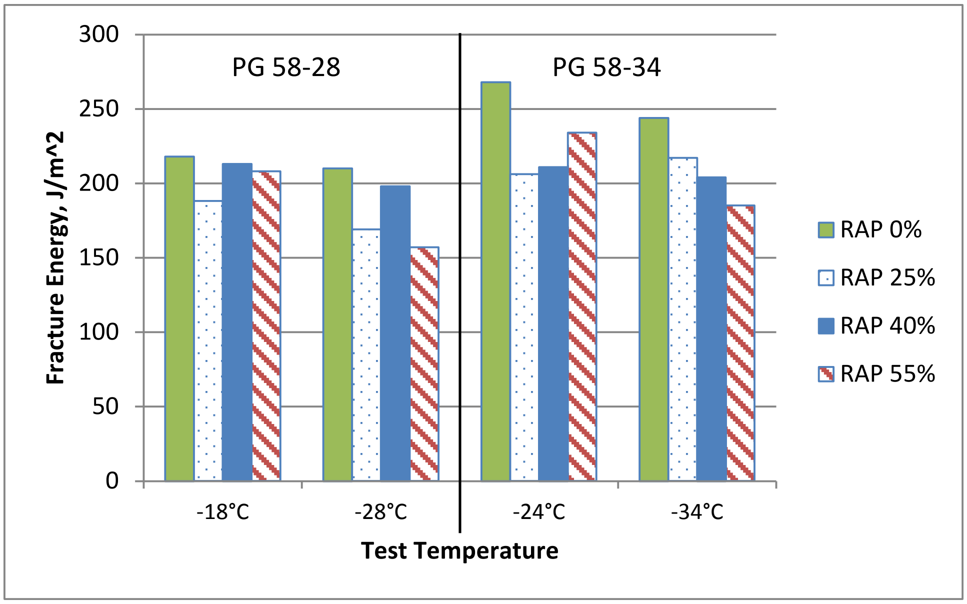


Figure 24: SCB Fracture Energy

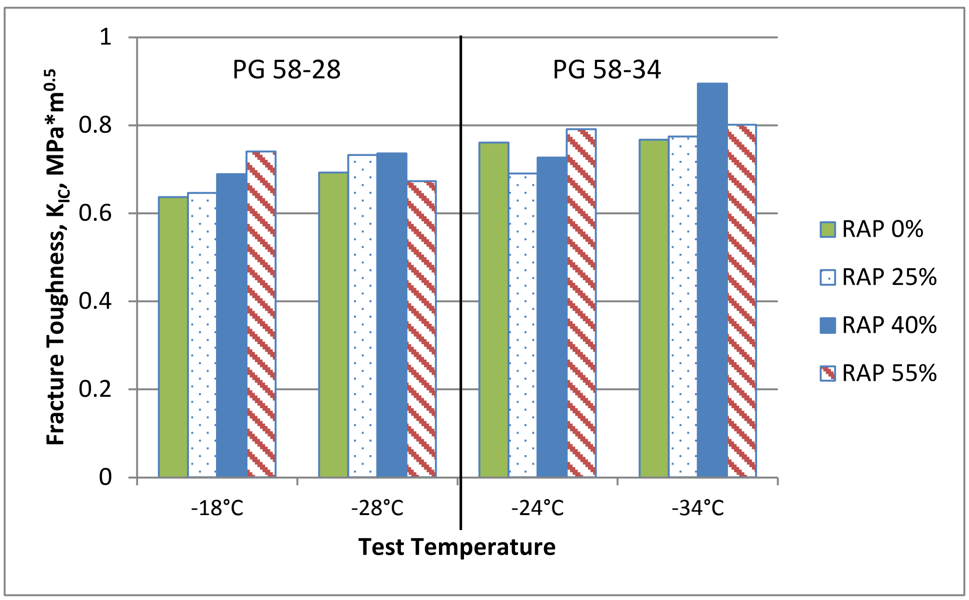


Figure 25: SCB Fracture Toughness

Back-calculation of Asphalt Binder Properties from IDT Mixture Testing

The *Huet* model and *ENTPE* (Ecole Nationale des Travaux Public de l'Etat) transformation were used to back-calculate the asphalt binder creep compliance, *D(t)* and its inverse creep stiffness, *S(t)*, from IDT mixture testing results. An introduction to the *Huet* model and *ENTPE* is presented in Appendix D.

The back-calculation was performed for PG + 10°C conditions. Binder stiffness results for S(60s) and S(500s) are shown in Table 19.

Table 19: Back-Calculated Asphalt Binder Stiffness, S(60s) and S(500s)

Binder	RAP, %	T, ºC	S(60s), MPa	S(500s), MPa
58-28	0	-18ºC	251	112
	25		425	251
	40		609	383
	55		609	371
58-34	0	-24ºC	262	136
	25		453	273
	40		692	459
	55		679	435

From the table it is evident that the binder stiffness of all mixtures increased along with an increase in RAP, much like creep stiffness results from mixture IDT testing. The trend appeared to plateau as RAP percentages moved from 40 to 55 percent.

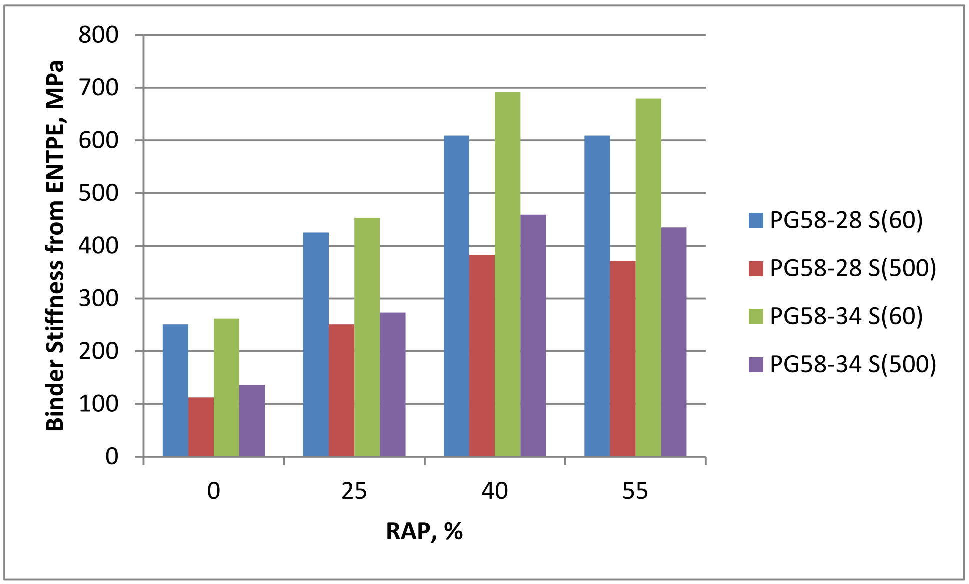


Figure 26: Back-Calculated Binder Stiffness by PG and RAP Content

There was a similarity between 0 percent RAP mixtures evaluated at 60 seconds and 25 percent RAP mixtures evaluated at 500 seconds. Back-calculated stiffness for both groups was near 250 MPa.

Conclusions from Low Temperature Testing

Based on the testing done the following can be concluded:

- For IDT strength, in most cases the RAP mixtures have slightly higher strength values than the control mixture, except for the results obtained for the 58-34 binder mixtures tested at PG temperature, for which the control was stronger than the RAP mixtures.
    - IDT strength trends were used in determining critical mixture temperature.

- From the limited Tcr data, it can be observed that the control mixture with the -34 binder has a critical temperature lower by more than 10ºC than the mixture with the -28 binder. It can be also seen that the addition of RAP significantly increases the critical temperature for the -34 binder, which may imply less crack resistance.
    - Based on results for these mixtures, it is expected that none of the RAP-bearing mixtures would outperform the non-RAP controls.
    - At the 1°C/hour cooling rate, 25 and 40 percent RAP mixtures made with Low PG -34 binder produced critical temperatures similar to the low PG-25 control mixture, predicting similar low temperature performance.
- For IDT creep stiffness, at PG + 10ºC the mixtures were ranked in the order of the RAP content: the higher the content the higher the stiffness at both 60s and 500s. At PG temperature, the differences between mixtures diminished; however, the mixture with 55 percent RAP still had the highest values at both 60s and 500s.
    - Reduced stiffness occurred when using low PG-34 relative to low PG-28. The relative stiffness reduction was observed for 0 and 25 percent RAP along with PG 58-34 binder. There was no reduction observed for the 40 percent RAP mixture.
- For SCB fracture testing, the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, in particular at the lowest test temperature of PG. For most cases, the highest RAP content appeared to be the most detrimental to fracture properties, in particular at the lowest temperature. Mixtures were not designed to achieve any suggested minimum fracture criteria proposed by other research.
    - No mixture achieved the minimum toughness and energy criteria recommended for good low temperature performance.
- The back-calculated binder stiffness values increased with increase in RAP content.
    - A similarity was observed between 0 percent RAP mixtures evaluated at 60 seconds and 25 percent RAP mixtures evaluated at 500 seconds.

Chapter 6. Summary and Conclusion

This investigation of high RAP asphalt mixtures included collaborative research between county and state road agencies, the asphalt paving industry, and academia. For the purpose of this investigation, the term "high RAP" refers to mixtures having 30 percent RAP or more. The following outcomes were determined for the major objectives of the investigation.

Expected Performance of Local Roads Built with Standard Amounts of RAP

A data set was developed using information supplied by county engineers. The county data contained a high frequency of designs having 20 to 26 percent RAP constructed with two asphalt binders; PG 52-34 and PG 58-28. A comparison of cracking performance showed there was a relative decrease of 40 percent in the number of cracks per mile and improved crack spacing of 34 percent for mixtures using the PG 52-34 binder. Based on a reduced data set from the five counties participating in this study, a statistical analysis found cracking performance was most affected by age and the percentage of new asphalt binder in the mixture.

Investigation of Activation of RAP Asphalt in Plant and Laboratory Settings

With the help of the asphalt industry, combinations of aggregate and normal levels (10 to 23 percent) of RAP were run through a batch plant at normal mixing conditions. No asphalt binder was added to the blends. An evaluation of asphalt coating (AASHTO T 195-67 modified) showed that plant mixing produced over 50 percent coating in the coarse aggregate fraction. Small batches of similar aggregate-RAP blends were mixed in the laboratory and evaluated for coating effectiveness. The effect of plant mixing was not directly replicated, but it was found that coarse aggregates from plant mixing achieved a more uniform coating and indicated less abrasion than those from laboratory mixing.

As part of the analysis, linear models were fitted to plant and laboratory coating data in order to learn about the effect of various parameters on the level of coating. It was determined that, with these materials and conditions, Temperature, Mixing Time, and Heating Time of RAP were the most influential parameters for complete coating in laboratory mixing situations; supporting field observations from the plant mixing phase. The percentage of RAP was also found important in explaining the amount of partial coating found on coarse aggregates.

High-RAP Mixture Development and Low-Temperature Performance Testing

Eight mixture designs were produced for laboratory evaluations. The designs used PG 58-28 and PG 58-34 asphalt binders with RAP contents ranging from 0 to 55 percent, and with New/Total asphalt cement ratios ranging from 43 to 100 percent. PG 58-28 and 58-34 were used in the lab because high PG performance was not evaluated in this study, and that variable could be eliminated. Other research has reported that PG 58-28 is the most common binder choice in Minnesota for mixtures with or without RAP, so high PG was fixed to the common value and low PG was varied in an attempt to evaluate any low temperature performance benefit.

Indirect tensile (IDT) testing for strength and creep, and semi-circular bend (SCB) testing for fracture energy and toughness, was performed at the low PG grade and at the low PG + 10ºC. IDT creep stiffness results showed that stiffness increased with RAP content. This effect was more pronounced at low PG + 10ºC than at low PG conditions. RAP mixtures also had slightly higher strength values than the control mixture, except for the 58-34 binder mixtures tested at PG temperature, for which the control was stronger than the RAP mixtures. A comparison of creep stiffness across binder grade showed that performance benefits from substituting low PG-34 for low PG-28 persist when using more than 25, but less than 40, percent RAP. Thus, “high RAP” mixtures experienced no benefit from grade substitution.

IDT critical temperatures (Tcr) were determined from the intersection of IDT strength and thermal stress curves. Tcr data was limited as a result of non-intersecting curves in many of the RAP mixtures, where strengths were substantially lower than the stress data. This was explained by the increase in stiffness and reduction in relaxation due to the addition of RAP. It was observed that the control mixture with the low PG-34 binder had a critical temperature lower by more than 10ºC than the mixture with the low PG-28 binder. It was also observed that the addition of RAP substantially increased the critical temperature for the PG 58-34 binder, predicting less crack resistance. A comparison of Tcr across binder grade at the rate of 1°C/hour showed that performance benefits from substituting low PG-34 for low PG-28 persist when using up to 40 percent RAP. Thus, “high RAP” mixtures experienced a benefit from grade substitution.

SCB fracture testing showed that the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, in particular at the lowest test temperature of PG. For most cases, the highest RAP content appeared to be the most detrimental to fracture properties, in particular at the lowest temperature. None of the mixtures met minimum recommended levels for fracture toughness or energy.

The back-calculated binder stiffness values increased with increase in RAP content. A similarity was observed between 0 percent RAP mixtures evaluated at 60 seconds and 25 percent RAP mixtures evaluated at 500 seconds, but this represented no benefit for performance.

Conclusion

Research on county data showed that, of the variables that can be controlled during design, the relationship of percent new asphalt binder contained in an asphalt mixture was related to field performance (cracking). Laboratory mixtures having 43 to 100 percent new asphalt binder (55 to 0 percent RAP), and two asphalt binder grades, were evaluated for low temperature performance with IDT and SCB testing. IDT results generally showed similar low temperature performance between mixtures containing PG 58-28 and no RAP versus those with PG 58-34 and 74 percent new binder (25 percent RAP). It is recommended that, when low temperature performance better than PG 58-28 is desired, low PG-34 binder may be substituted and used in percentages greater than 74 percent of total binder (approximately 25% RAP). This consideration would often apply to use in wear-courses, so similar research could be performed to establish guidelines for non-wear scenarios.

It was found that the coating transfer of RAP asphalt in laboratory conditions occurred at much lower levels that those from industrial scale plant conditions. However, RAP heating temperature and the duration of mixing and heating influenced coating transfer, so designers could increase the values of these parameters to practical maximums in order to better mimic the results from plant conditions.

References

1. Minnesota Department of Transportation, Standard Specifications for Construction, *2360: Plant Mixed Asphalt Pavement, Gyratory Design Specification, January 23, 2013*, http://www.dot.state.mn.us/materials/bituminousdocs/Specifications/2013/2360-2013__Fina_1-23-2013.pdf. Minnesota Department of Transportation Office of Materials and Road Research, Maplewood, MN, accessed March 1, 2013.

2. E. Johnson, G. Johnson, S. Dai, D. Linell, J. McGraw and M. Watson, *Incorporation of Recycled Asphalt Shingles in Hot-Mixed Asphalt Pavements*, Report MN/RC 2010-08. Minnesota Department of Transportation, Saint Paul, MN, 2010.

3. AASHTO, *Standard Method of Test for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures AASHTO T 195-67*. American Association of State and Highway Transportation Officials, Washington, D.C., 2005.

4. Arc, Version 1.06, July 2004. © R. Dennis Cook and Sanford Weisberg 1999-2004.

5. E. Johnson and R. Olson, *Best Practices for RAP Use Based on Field Performance*. Minnesota Department of Transportation, St. Paul, MN, 2009.

6. M. Marasteanu, A. Zofka, M. Turos, X. Li, R. Velasquez, X. Li, W. Buttlar, G. Paulino, A. Braham, E. Dave, J. Ojo, H. Bahia, C. Williams, J. Bausano, A. Gallistel, and J. McGraw, *Investigation of Low Temperature Cracking in Asphalt Pavements,* National pooled Fund Study 776. Minnesota Department of Transportation, St. Paul, MN, 2007.

7. M. Marasteanu, K. H. Moon, and M. Turos, *Asphalt Mixture and Binder Fracture Testing for 2008 MnROAD Construction*, Final Report. Minnesota Department of Transportation Research Service MS 330, St. Paul, MN, 2009.

8. K. H. Moon, *Comparison of Thermal Stresses Calculated from Asphalt Binder and Asphalt Mixture Creep Compliance Data,* Master Thesis. University of Minnesota Department of Civil Engineering, Minneapolis, MN, 2010.

9. X. Li, *Investigation of the Fracture Resistance of Asphalt Mixtures at Low Temperature with a Semi Circular Bend (SCB) Test*, Ph.D. Thesis. University of Minnesota, Minneapolis, MN, 2005.

10. M. Marasteanu, W. Buttlar, K. H. Moon, E. Dave, E. Teshale, G. Paulino, A. Cannone Falchetto, S. Ahmed, M. Turos, S. Leon, A. Braham, B. Behnia, H. Bahia, H. Tabatabaee, C. Williams, R. Velasquez A. Buss, A. Arshadi, J. Bausano, S. Puchalski, A. Kvasnak, S. Mangiafico, *Investigation of Low Temperature Cracking in Asphalt Pavements,* National Pooled Fund Study - Phase II. Minnesota Department of Transportation Research Service MS 330, St. Paul, MN, 2012.

11. C. Huet, *Etude par une méthode d'impédance du comportement viscoélastique des matériaux hydrocarbonés*, Thèse de doctorat d'ingénieur. Faculté des Sciences de l'Université de Paris, October 1963.

12. A. Cannone Falchetto, M. Marasteanu, and H. Di Benedetto, "Analogical Based Approach to Forward and Inverse Problems for Asphalt Materials Characterization at Low Temperature". Journal of the Association of Asphalt Paving Technologists, DEStech Publications, Inc., Lancaster, PA, 2011.

13. H. Di Benedetto, F. Olard, C. Sauzéat, and B. Delaporte, "Linear Viscoelastic Behaviour of Bituminous Materials: from Binders to Mixes", Road Material and Pavement Design, vol. 5 – Special Issue, pp.163-202, 2004. http://www.tandfonline.com/doi/abs/10.1080/14680629.2004.9689992, accessed March 1, 2013.

Appendix A: County Performance Survey Results

County highway performance data was developed from a combination of video-log reviews and field inspections. The data was categorized by design asphalt Performance Grade, and averages were calculated for RAP content, design and add AC percentages, age, ratio of new to total AC, cracks per mile, and the spacing between cracks (as normalized by section length). The results are tabulated in the following table.

County Road Performance Data

County	Road	Construction Year	Type, (lift in.)	MDR	RAP	PG	Total AC	Add AC	Cracks	Length, miles	Notes	Section Limits
Dodge	15	1999	Wear (2)	06-990077	0	58-28	6.1	6.1	14	1.51	none	1270 m to 3696.5 m east of TH 57
Dodge	15	1999	Nonwear (2)	06-990067	0	58-28	5.8	5.8	14	1.51	none	1270 m to 3696.5 m east of TH 57
Dodge	15	1999	Wear (2)	06-990138	18	58-28	5.2	4.48	38	0.273	none	830 m to 1270 m east of TH 57
Dodge	15	1999	Nonwear (2)	06-990140	15	58-28	5.4	4.8	38	0.273	none	830 m to 1270 m east of TH 57
Dodge	15	1999	Wear (1.5)	06-990138	18	58-28	5.2	4.48	90	0.508	none	east from TH 57
Dodge	15	1999	Nonwear (2.5)	06-990140	15	58-28	5.4	4.8	90	0.508	none	east from TH 57
Dodge	15	2003	Wear (2.3)	06-2003-112	20	58-28	5.5	4.7	524	3.978	none	TH 30 to CSAH6
Dodge	15	2003	Nonwear (2.5)	06-2003-112	20	58-28	5.5	4.7	524	3.978	none	TH 30 to CSAH6
Dodge	2	2005	Wear (1.5)	06-2005-141	20	58-34	5.5	4.3	17	6.039	none	West County line to CSAH5
Dodge	2	2005	Nonwear (2.5)	06-2005-141	20	58-34	5.5	4.3	17	6.039	none	West County line to CSAH5
Dodge	25	2002	Wear (1.5)	06-2002-133	0	64-28	6.2	6.2	4	0.241	none	DM&E railroad to CSAH34 in Dodge Center
Dodge	25	2002	Nonwear (2.5)	06-2002-119	10	58-28	5.6	5.2	4	0.241	none	DM&E railroad to CSAH34 in Dodge Center
Dodge	7	2003	Wear (1.5)	06-2003-0??	0	58-28	6.1	6.1	410	4.872	none	CSAH16 to CSAH24
Dodge	7	2003	NonWrBase (2.5)	06-2003-069	15	58-28	6	5.4	410	4.872	none	CSAH16 to CSAH24
Dodge	7	2003	Nonwear (2)	06-2003-069	15	58-28	6	5.4	410	4.872	none	CSAH16 to CSAH24

Dodge	7	2003	Wear (1.5)	06-2003-0??	0	58-28	6.1	6.1	766	3.196	none	CSAH24 and Goodhue county line
Dodge	7	2003	Nonwear (2.5)	06-2003-069	15	58-28	6	5.4	766	3.196	none	CSAH24 and Goodhue county line
Itasca	11	2009	Wear (1.5), 1	1-09-084	30	52-34	5.3	3.6	17	0.099	BOB	1+27 - 6+50
Itasca	11	2009	Wear (0.5), 2	1-09-083	30	52-34	5.6	4.1	17	0.099	BOB	1+27 - 6+50
Itasca	11	2009	bridge deck, exclude							skip	skip	127+16 - 127+81
Itasca	11	2009	Wear (1.5), 1	1-09-084	30	52-34	5.3	3.6	100	0.626	BOB	127+81 - 160+87
Itasca	11	2009	Wear (0.5), 2	1-09-083	30	52-34	5.6	4.1	100	0.626	BOB	127+81 - 160+87
Itasca	11	2009	Wear (1.5), 1	1-09-084	30	52-34	5.3	3.6	1	0.044	BAB	160+87 - 163+17
Itasca	11	2009	Wear (0.5), 2	1-09-083	30	52-34	5.6	4.1	1	0.044	BAB	160+87 - 163+17
Itasca	11	2009	Wear (3.0), 3	1-09-084	30	52-34	5.3	3.6	1	0.044	BAB	160+87 - 163+17
Itasca	11	2009	Wear (1.5), 1	1-09-084	30	52-34	5.3	3.6	337	3.11	BOB	163+17 - 327+36
Itasca	11	2009	Wear (0.5), 2	1-09-083	30	52-34	5.6	4.1	337	3.11	BOB	163+17 - 327+36
Itasca	11	2009	Wear (3.0), 1	1-09-084	30	52-34	5.3	3.6	130	5.1	CIR 4-in.	327+36 - 596+64
Itasca	11	2009	Wear (1.5), 1	1-09-084	30	52-34	5.3	3.6	499	2.285	BOB	6+50 -127+16
Itasca	11	2009	Wear (0.5), 2	1-09-083	30	52-34	5.6	4.1	499	2.285	BOB	6+50 -127+16
Itasca	11	2006	Wear (1.5), 1	1-06-046	20	52-34	4.8	3.9	127	5.45	FDR 6-in.	7+00 - 295+68
Itasca	11	2006	Nonwear (4.0). 2	1-06-004	20	52-34	5.2	4.3	127	5.45	FDR 6-in.	7+00 - 295+68
Itasca	19	2006	Wear (1.5), 1	SAP 31-619-08	30	52-34	no data	no data	34	1.018	FDR 8-in.	0+00 - 53+73
Itasca	19	2006	Nonwear (2.5), 2	SAP 31-619-08	40	52-34	no data	no data	34	1.018	FDR 8-in.	0+00 - 53+73
Itasca	19	2006	Wear (1.5),	SAP 31-619-	30	52-34	no	no	115	2.839	FDR	53+73 - 203+64

			1	08			data	data			6-in.	
Itasca	19	2006	Nonwear (2.5), 2	SAP 31-619-08	40	52-34	no data	no data	115	2.839	FDR 6-in.	53+73 - 203+64
Itasca	35	2009	bridge deck, exclude							skip	skip	0+00 - 1+27
Itasca	4	2007	Wear (1.5), 1	1-07-054	30	58-28	5.3	3.6	51	1.837	FDR 6-in.	0+00 - 97+00
Itasca	4	2007	Nonwear (4.0), 2	1-07-053	40	58-28	5.2	3	51	1.837	FDR 6-in.	0+00 - 97+00
Itasca	4	2007	Wear (1.5), 1	1-07-054	30	58-28	5.3	3.6	109	2.727	BOB milled	5280+00 - 672+00
Itasca	4	2007	Nonwear (4.0), 2	1-07-053	40	58-28	5.2	3	109	2.727	BOB milled	5280+00 - 672+00
Itasca	4	2007	Wear (1.5), 1	1-07-054	30	58-28	5.3	3.6	88	2.765	FDR 4-in.	672+00 - 818+00
Itasca	4	2007	Nonwear (4.0), 2	1-07-053	40	58-28	5.2	3	88	2.765	FDR 4-in.	672+00 - 818+00
Itasca	4	2007	Wear (1.5), 1	1-07-054	30	58-28	5.3	3.6	225	8.163	FDR 4-in.	97+00 - 528+00
Itasca	4	2007	Nonwear (4.0), 2	1-07-053	40	58-28	5.2	3	225	8.163	FDR 4-in.	97+00 - 528+00
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	14	1.019	SFDR 4-in. FDR 2.5-in.	121+50 - 175+30
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	3	0.04	SFDR 4-in.	175+30 - 177+40
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	3	0.04	SFDR 4-in.	175+30 - 177+40
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	1	0.303	SFDR 4-in. FDR 2.5-in.	177+40 - 193+41
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	1	0.303	SFDR 4-in. FDR 2.5-in.	177+40 - 193+41
Itasca	8	2009	Wear (1.5),	1-09-054	30	52-34	5.4	4	9	0.381	SFDR	204+65.09 - 224+75

			1								4-in. FDR 2.5-in.	
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	9	0.381	SFDR 4-in. FDR 2.5-in.	204+65.09 - 224+75
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	1	0.037	SFDR 4-in.	224+75 - 226+70
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	1	0.037	SFDR 4-in.	224+75 - 226+70
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	25	0.848	SFDR 4-in. FDR 2.5-in.	226+70 - 271+50
Itasca	8	2009	Wear (2.5), 2	1-09-053	30	52-34	5.1	3.8	25	0.848	SFDR 4-in. FDR 2.5-in.	226+70 - 271+50
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	14	1.019	SFDR 4-in. FDR 2.5-in.	250' S of CSAH56; 121+50 - 175+30
Itasca	8	2009	Wear (1.5), 1	1-09-054	30	52-34	5.4	4	22	0.199	BOB (1.5 + 5)	271+50 - 282+00; 800' E of CSAH58
Olmsted	13	2004	Nonwear (2.5), 2	06-2004-094	20	58-34	5.5		0	2.11	none	W. county Line to CSAH3
Olmsted	13	2004	Wear (1.5), 1	06-2004-093	20	58-34	5.9		0	2.11	none	W. county Line to CSAH3
Olmsted	21	2005	Nonwear (2.5), 2	06-2005-079	20	58-34	5.7		9	4.892	none	TH 63 to East County Line
Olmsted	21	2005	Wear (1.5), 1	06-2005-080	20	58-34	5.7		9	4.892	none	TH 63 to East County Line
Pope	22	2005	Wearing (1.5”)	04-2005-033	0	52-34	6.1	6.1	80	2.059	none	CSAH33 S. to county line
Pope	22	2005	Nonwear (2.0”)	04-2005-032	20	52-34	5.6	4.6	80	2.059	none	CSAH33 S. to county line
Pope	28	2007	Wearing (1.5”)	04-2007-21	15	52-34	no mdr	no mdr			none	CR 79 to TH 55

Pope	28	2007	Nonwear (2.0")	04-2007-21	25	52-34	no mdr	no mdr			none	CR 79 to TH 55
Pope	29	2004	Wearing (1.5")	04-2004-004	0	52-34	5.9	5.9	170	4.999	none	TH 104 to TH 55
Pope	29	2004	Nonwear (2.0")	04-2004-006	20	52-34	5.8	5.2	170	4.999	none	TH 104 to TH 55
Pope	32	2003	Wearing (1.5")	04-2003-059	0	52-34	6.3	6.3	56	1.12	none	West County Line to CSAH3
Pope	32	2003	Nonwear (2.0")	04-2003-058	20	52-34	5.8	4.8	56	1.12	none	West County Line to CSAH3
Wilkin	19	2007	Wear	04-2007-019	0	no data	5.7	5.7			none	no data
Wilkin	19	2007	Nonwear	04-2007-019	0	no data	5.7	5.7			none	no data
Wilkin	14	2004			0	no data			350	7.808	none	
Wilkin	612	2004	Nonwear	04-2004-015	0	no data	6	6			none	no data
Wilkin	614	2004	Nonwear	04-2004-015	0	no data	6	6			none	no data
Wilkin	621	2006	Wear	04-2006-008	0	no data	6	6			none	no data
Wilkin	621	2006	Nonwear	04-2006-008	0	no data	6	6			none	no data

Appendix B: Test Matrix for the Laboratory RAP Activation Study, Linear Regression Results for RAP Activation Data

Test Matrix for Laboratory RAP Activation Trials

Mix	3/4 Rock	Man Sand	Nat Sand	CastleR 1/2x4	RAP	TOTAL	% RAP	Heat Agg, deg F	Heat RAP, min	Mix Time, min
Batch 23A0	600	625	700		575	2500	23%	72	0	10
Batch 23A1	600	625	700		575	2500	23%	290	180	1
Batch 23A2	600	625	700		575	2500	23%	290	180	5
Batch 23B1	600	625	700		575	2500	23%	290	90	10
Batch 23B2	600	625	700		575	2500	23%	290	90	10
Batch 23C1	600	625	700		575	2500	23%	290	1	10
Batch 23C2	600	625	700		575	2500	23%	290	1	10
Batch 23D1	600	625	700		575	2500	23%	320	1	10
Batch 23D2	600	625	700		575	2500	23%	320	1	10
Batch 23E1	600	625	700		575	2500	23%	320	160	10
Batch 23E2	600	625	700		575	2500	23%	320	170	10
Batch 10A1	600	625	700		213.9	2138.9	10%	290	180	1
Batch 10A2	600	625	700		213.9	2138.9	10%	290	180	5
Batch 10B1	600	625	700		213.9	2138.9	10%	290	90	10
Batch 10B2	600	625	700		213.9	2138.9	10%	290	90	10
Batch 10C1	600	625	700		213.9	2138.9	10%	290	1	10
Batch 10C2	600	625	700		213.9	2138.9	10%	290	1	10
Batch 10D1	600	625	700		213.9	2138.9	10%	320	10	10
Batch 10D2	600	625	700		213.9	2138.9	10%	320	20	10
Batch 10E1	600	625	700		213.9	2138.9	10%	320	180	10
Batch 10E2	600	625	700		213.9	2138.9	10%	320	190	10
Batch 100A					500	500	100%	320	90	5
PlantRun1	28%	29%	33%		10%	100%	10%	420	0.5	0.5
PlantRun2	24%	25%	28%		23%	100%	23%	490	0.5	0.5
PlantRun2 washed	24%	25%	28%		23%	100%	23%	490	0.5	0.5
PlantRun3	24%	25%	28%		23%	100%	23%	400	0.5	0.5
Batch 23Y1	3600	3750	4200		3450	15000	23%	300	100	3
Batch 23Z1	3600	3750	4200		3450	15000	23%	300	0	3
Batch 50Z1				7500	7500	15000	50%	300	100	3
Batch 23Z2	3600	3750	4200		3450	15000	23%	300	120	2

Completely Coated Regression Model

Multiple linear regression for Completely Coated Aggregate ("CCoat") as a function of Total Aggregate less than 3/8-in. ("Total"), Temperature of Aggregates ("AggF"), Percent RAP ("RAP"), Mixing Time ("TMIX"), and Heating Time of RAP ("TRAP").

```
Data set = RAP_Transfer, Name of Fit = L1
Normal Regression
Kernel mean function = Identity
Response      = "Ccoat"
Terms         = ("Total" "AggF" "RAP" "TMIX "TRAP")
Coefficient Estimates
Label       Estimate        Std. Error    t-value    p-value
Constant   -124.531         26.1277        -4.766     0.0001
"Total"     0.646399        0.0340366      18.991     0.0000
"AggF"     -0.0640250       0.0660096      -0.970     0.3437
"RAP"       1.40227         0.213799        6.559     0.0000
"TMIX       0.847644        1.37449         0.617     0.5444
"TRAP"      0.0484387       0.0548352       0.883     0.3875

R Squared:                0.986097
Sigma hat:                 16.9433
Number of cases:               26
Degrees of freedom:            20

Summary Analysis of Variance Table
Source         df       SS            MS           F     p-value
Regression      5    407225.       81444.9     283.70    0.0000
Residual       20    5741.53       287.077
```

Partially Coated Regression Model

Multiple linear regression for Partially Coated Aggregate ("PCoat") as a function of Total Aggregate less than 3/8-in. ("Total"), Temperature of Aggregates ("AggF"), Percent RAP ("RAP"), Mixing Time ("TMIX"), and Heating Time of RAP ("TRAP").

```
Data set = RAP_Transfer, Name of Fit = L2
Normal Regression
Kernel mean function = Identity
Response      = "Pcoat"
Terms         = ("Total" "AggF" "RAP" "TMIX "TRAP")
Coefficient Estimates
Label       Estimate        Std. Error    t-value    p-value
Constant   -87.6224         43.7892        -2.001     0.0591
"Total"     0.449620        0.0570443       7.882     0.0000
"AggF"      0.306171        0.110630        2.768     0.0119
"RAP"      -0.0493815       0.358321       -0.138     0.8918
"TMIX      -4.11832         2.30361        -1.788     0.0890
"TRAP"     -0.169527        0.0919021      -1.845     0.0800

R Squared:                0.962862
Sigma hat:                 28.3965
Number of cases:               26
Degrees of freedom:            20

Summary Analysis of Variance Table
Source         df       SS            MS           F     p-value
Regression      5    418121.       83624.2     103.71    0.0000
Residual       20    16127.2       806.362
```

Uncoated Regression Model

Multiple linear regression for Uncoated Aggregate ("UCoat") as a function of Total Aggregate less than 3/8-in. ("Total"), Temperature of Aggregates ("AggF"), Percent RAP ("RAP"), Mixing Time ("TMIX"), and Heating Time of RAP ("TRAP").

```
Data set = RAP_Transfer, Name of Fit = L3
Normal Regression
Kernel mean function = Identity
Response      = "Ucoat"
Terms         = ("Total" "AggF" "RAP" "TMIX "TRAP")
Coefficient Estimates
Label       Estimate        Std. Error    t-value    p-value
Constant    212.154         37.7758         5.616     0.0000
"Total"    -0.0960198       0.0492107      -1.951     0.0652
"AggF"     -0.242146        0.0954377      -2.537     0.0196
"RAP"      -1.35289         0.309114       -4.377     0.0003
"TMIX       3.27067         1.98726         1.646     0.1154
"TRAP"      0.121088        0.0792815       1.527     0.1423

R Squared:               0.860107
Sigma hat:                24.4969
Number of cases:               26
Degrees of freedom:            20

Summary Analysis of Variance Table
Source         df       SS           MS          F     p-value
Regression      5    73792.3      14758.5      24.59    0.0000
Residual       20     12002.        600.1
```

Appendix C: High-RAP Mixture Designs

Design worksheets for the preliminary designs are given in the following figures, including:

- Design Sheets. Design sheets were used to produce trial gradations and asphalt percentages using individual product gradation data, target void content, and target VMA. The resulting designs are charted on the Gradation Plot.
- Gradation Plots. Gradation plots show the trial aggregate mixture blends produced on the Design Sheet.
- Materials quantity requirements are laid out in one or more Batching Sheets. The Batching Sheets that are provided give alternatives for producing laboratory mixtures of 10,000 grams or 15,000 grams.

Date: 02/10/11

BATCHING SHEET

Agency:

Trial Mix: U OF M MIX VIRGIN MIX

Material	50.0 2"	37.50 1 1/2"	25 1"	19 3/4	12.5 1/2	9.5 3/8	4.75 #4	2.36 #8	1.18 #16	0.60 #30	0.30 #50	0.15 100	0.075 #200	%Ins
rap	100.0	100.0	100.0	100.0	94.0	87.0	69.0	55.0	44.0	32.0	18.0	10.0	6.6	
scandia screen sa	100.0	100.0	100.0	100.0	100.0	99.0	97.0	90.0	78.0	54.0	27.0	7.0	3.0	100
3/4 kram cle	100.0	100.0	100.0	100.0	60.0	37.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	100
limesand	100.0	100.0	100.0	100.0	100.0	100.0	99.0	75.0	48.0	33.0	19.0	6.0	3.0	100
Om Toss	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	85.0	65.0	49.0	35.0	24.1	100
KRMoss	100.0	100.0	100.0	100.0	100.0	100.0	98.0	97.0	81.0	61.0	52.0	40.0	30.9	
coarse rap	**100.0**	**100.0**	**100.0**	**90.0**	**70.0**	**58.0**	**36.0**							
ER#2 BA3/	100.0	100.0	100.0	100.0	90.0	83.0	70.0	61.0	45.0	34.0	28.0	13.0	3.8	
h														
i														
j														

VMA	Max Size	Air Voids
37.00	0.75	4.00

target AC= **5.50**

For Recycled Mixtures; Asphalt Conte **5.60**

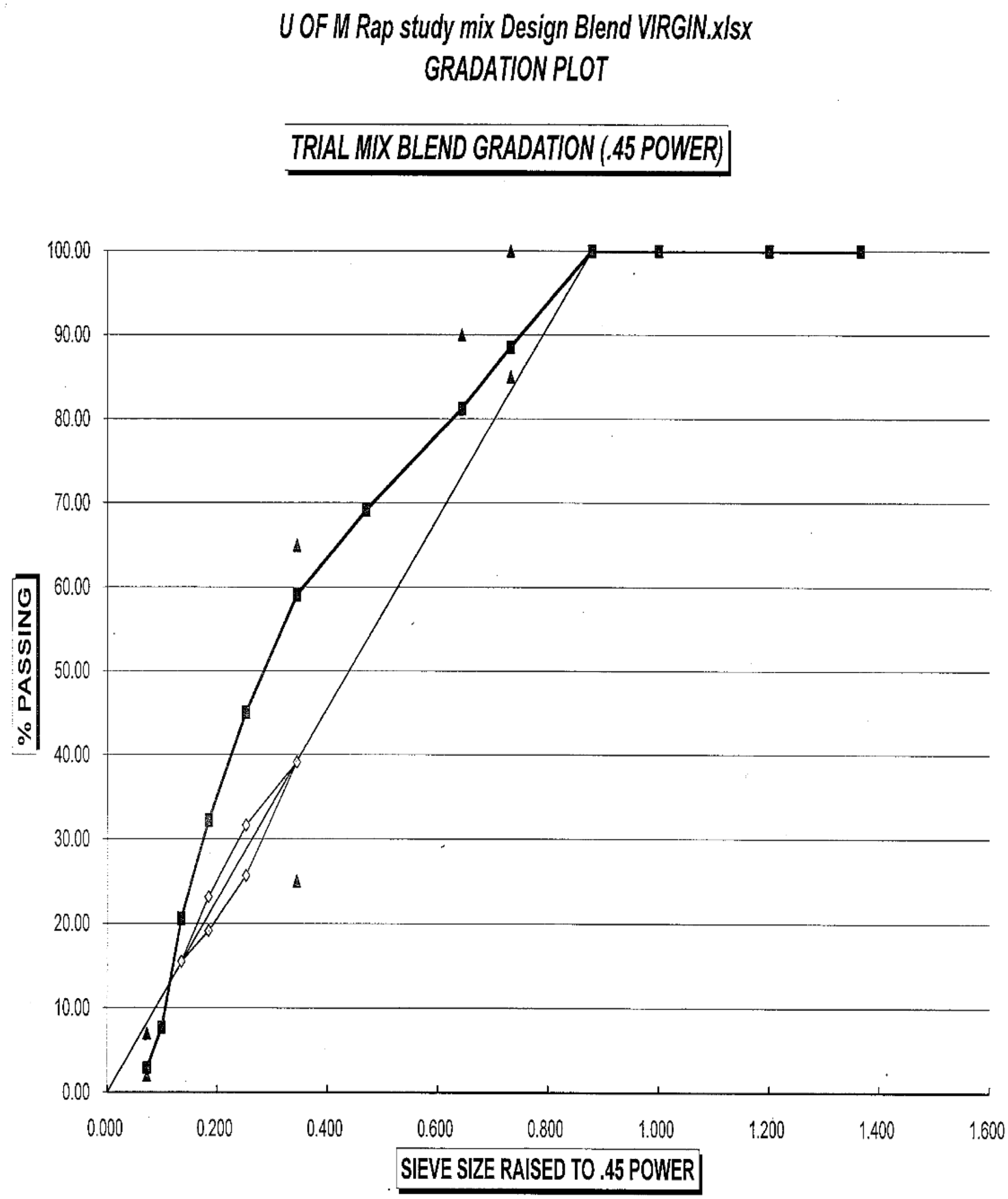
shingle AC= **0.00**

25.00 **Approxmiate VMA Trail Seed Values: 50mm 39, 37.5mm 38, 25mm 37.5, 19mm 37, 12.5mm 36.5 etc**

Cost Cal.	Cost Mat's	Trial %	50.0 2"	37.50 1 1/2"	25 1"	19 3/4	12.5 1/2	9.5 3/8	4.75 #4	2.36 #8	1.18 #16	0.60 #30	0.30 #50	0.15 100	0.075 #200	
0.00	rap	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	:reen sa	**25**	25	25	25	25	25	25	24	23	20	14	7	2	1	6.1
0.00	am clear	**20**	20	20	20	20	12	7	1	0	0	0	0	0	0	48.4
0.00	mesand	**20**	20	20	20	20	20	20	20	15	10	7	4	1	1	12.2
0.00	)m Toss	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	KRMoss	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	arse rap	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	:2 BA3/4	**35**	35	35	35	35	32	29	25	21	16	12	10	5	1	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**100.0**														
		JMF =	**100.0**	**100.0**	**100.0**	**100.0**	**88.5**	**81.2**	**69.2**	**59.1**	**45.1**	**32.2**	**20.6**	**7.7**	**2.9**	
		C Pts	100	100	100	100	85	35	30	25					2	
			100	100	100	100	100	90	80	65					7	
		Restricted								39.1	26	19	16			
		Zone								39.1	32	23	16			
		TARGET GRAD				100	89	81	67	56	44	31	17	6	3.6	

C:\Documents and Settings\line1dav\My Documents\U OF M Rap study mix Design Blend VIRGIN.xlsx

Design sheet for 0% RAP.



Trial mixture gradation: 0% RAP.

BATCHING SHEET

NEED (NEW)

U OF M MIX VIRGIN MIX BATCH WT = 15,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	ER#2 BA3/	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	25.0	20.0	20.0	0.0	0.0	0.0	35.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	1200.0	0.0	0.0	0.0	0.0	525.0	0.0	0.0	0.0	0.0 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	37.5	690.0	0.0	0.0	0.0	0.0	367.5	0.0	0.0	0.0	0.0 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	75.0	1020.0	30.0	0.0	0.0	0.0	682.5	0.0	0.0	0.0	0.0 = #4
#4 - #8	4.75 - 2.38 mm	0.0	262.5	60.0	720.0	0.0	0.0	0.0	472.5	0.0	0.0	0.0	0.0 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	450.0	0.0	810.0	0.0	0.0	0.0	840.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	900.0	0.0	450.0	0.0	0.0	0.0	577.5	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	1012.5	0.0	420.0	0.0	0.0	0.0	315.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	750.0	0.0	390.0	0.0	0.0	0.0	787.5	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	150.0	0.0	90.0	0.0	0.0	0.0	483.0	0.0	0.0	0.0	
PAN	PAN	0.0	112.5	30.0	90.0	0.0	0.0	0.0	199.5	0.0	0.0	0.0	
	TOTAL	0.00	3750.00	3000.00	3000.00	0.00	0.00	0.00	5250.00	0.00	0.00	0.00	15000.00
	TOTAL MINUS #4	0.0	3637.5	90.0	2970.0	0.0	0.0	0.0	3675.0	0.0	0.0	0.0	10372.5
	TOTAL MINUS #8	0.0	3375.0	30.0	2250.0	0.0	0.0	0.0	3202.5	0.0	0.0	0.0	8857.5

Calculate gms of AC for batch

% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.50	873.0		0.0	873.0
	0.0			
	0.0			

Batching sheet for 15,000 gram mix: 0% RAP.

BATCHING SHEET

U OF M MIX VIRGIN MIX BATCH WT = 10,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	ER#2 BA3/	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	25.0	20.0	20.0	0.0	0.0	0.0	35.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	800.0	0.0	0.0	0.0	0.0	350.0	0.0	0.0	0.0	0.0 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	25.0	460.0	0.0	0.0	0.0	0.0	245.0	0.0	0.0	0.0	0.0 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	50.0	680.0	20.0	0.0	0.0	0.0	455.0	0.0	0.0	0.0	0.0 =#4
#4 - #8	4.75 - 2.38 mm	0.0	175.0	40.0	480.0	0.0	0.0	0.0	315.0	0.0	0.0	0.0	0.0 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	300.0	0.0	540.0	0.0	0.0	0.0	560.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	600.0	0.0	300.0	0.0	0.0	0.0	385.0	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	675.0	0.0	280.0	0.0	0.0	0.0	210.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	500.0	0.0	260.0	0.0	0.0	0.0	525.0	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	100.0	0.0	60.0	0.0	0.0	0.0	322.0	0.0	0.0	0.0	
PAN	PAN	0.0	75.0	20.0	60.0	0.0	0.0	0.0	133.0	0.0	0.0	0.0	
	TOTAL	0.00	2500.00	2000.00	2000.00	0.00	0.00	0.00	3500.00	0.00	0.00	0.00	10000.00
	TOTAL MINUS #4	0.0	2425.0	60.0	1980.0	0.0	0.0	0.0	2450.0	0.0	0.0	0.0	6915.0
	TOTAL MINUS #8	0.0	2250.0	20.0	1500.0	0.0	0.0	0.0	2135.0	0.0	0.0	0.0	5905.0

Calculate gms of AC for batch				
% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.50	582.0		0.0	582.0
	0.0			
	0.0			

Batching sheet for 10,000 gram mix: 0% RAP.

Date: 02/10/11

Agency:

BATCHING SHEET

Location:

Trial Mix: U OF M MIX w/25% RAP

	50.0	37.50	25	19	12.5	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075	
Material	2"	1 1/2"	1"	3/4	1/2	3/8	#4	#8	#16	#30	#50	100	#200	%Ins
rap	100.0	100.0	100.0	100.0	94.0	87.0	69.0	55.0	44.0	32.0	18.0	10.0	6.6	
scandia screen sa	100.0	100.0	100.0	100.0	100.0	99.0	97.0	90.0	78.0	54.0	27.0	7.0	3.0	100
3/4 kram cle	100.0	100.0	100.0	100.0	60.0	37.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	100
limesand	100.0	100.0	100.0	100.0	100.0	100.0	99.0	75.0	48.0	33.0	19.0	6.0	3.0	100
Om Toss	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	85.0	65.0	49.0	35.0	24.1	100
KRMoss	100.0	100.0	100.0	100.0	100.0	100.0	98.0	97.0	81.0	61.0	52.0	40.0	30.9	
coarse rap	100.0	100.0	100.0	90.0	70.0	58.0	36.0							
g														
h														
i														
j														

VMA	Max Size	Air Voids
37.00	0.75	4.00

target AC= 5.40

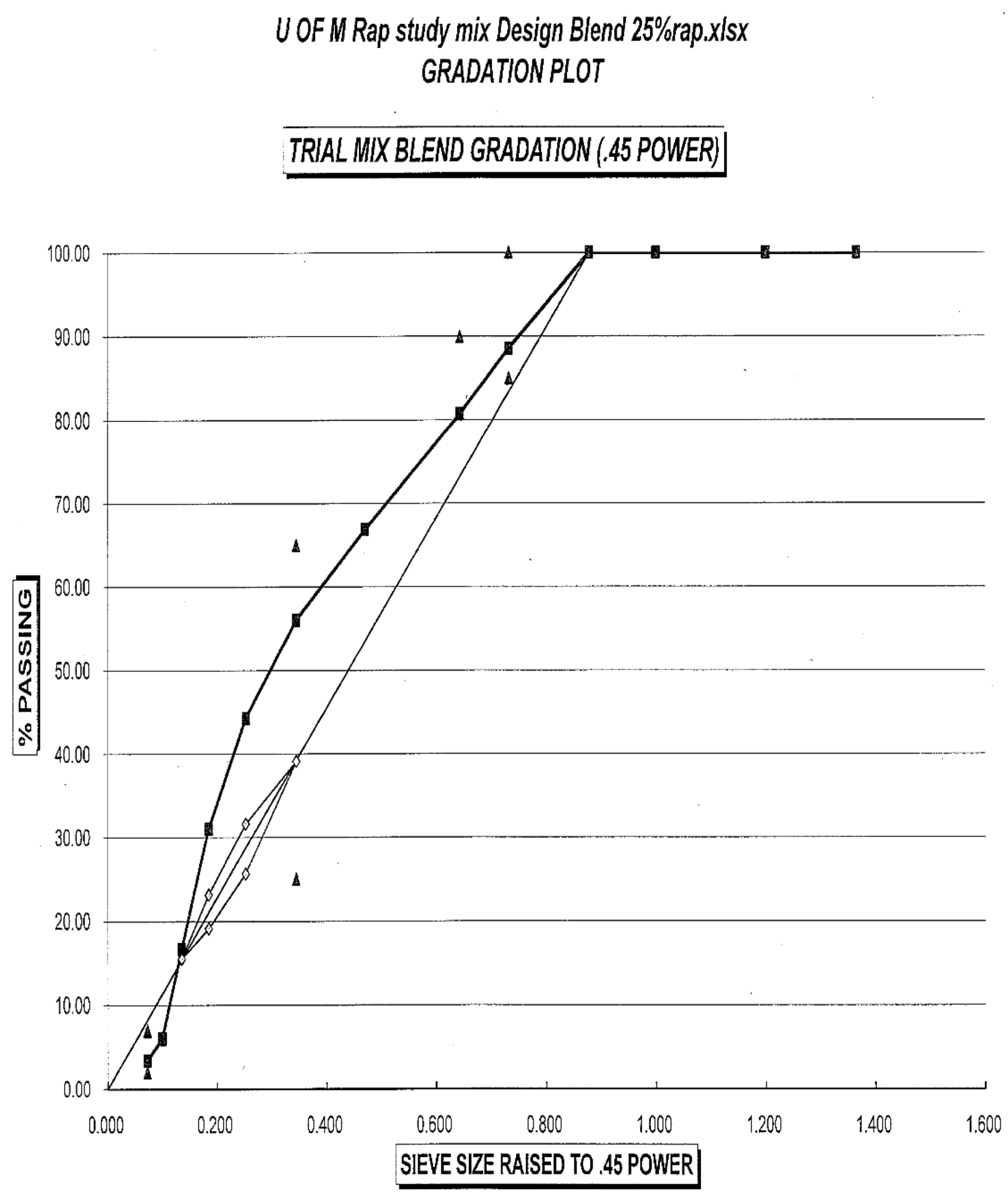
For Recycled Mixtures; Asphalt Conte 5.60

shingle AC= 0.00

		25.00	Approxmiate VMA Trail Seed Values:					50mm 39, 37.5mm 38, 25mm 37.5, 19mm 37, 12.5mm 36.5 etc								
Cost	Cost	Trial	50.0	37.50	25	19	12.5	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075	
Cal.	Mat's	%	2"	1 1/2"	1"	3/4	1/2	3/8	#4	#8	#16	#30	#50	100	#200	
0.00	rap	25	25	25	25	25	24	22	17	14	11	8	5	3	2	0.0
0.00	creen sa	30	30	30	30	30	30	30	29	27	23	16	8	2	1	6.8
0.00	am clear	25	25	25	25	25	15	9	1	0	0	0	0	0	0	56.3
0.00	mesand	20	20	20	20	20	20	20	20	15	10	7	4	1	1	11.4
0.00	Om Toss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	KRMoss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	arse rap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		100.0														
		JMF =	100.0	100.0	100.0	100.0	88.5	80.7	66.9	56.0	44.3	31.1	16.7	6.1	3.4	
		C Pts	100	100	100	100	85	35	30	25					2	
			100	100	100	100	100	90	80	65					7	
		Restricted								39.1	26	19	16			
		Zone								39.1	32	23	16			
		TARGET GRAD				100	89	[illegible]	67	56	44	31	17	6	3.6	

C:\Documents and Settings\line1dav\My Documents\U OF M Rap study mix Design Blend 20%rap.xlsx

Design sheet for 25% RAP.



Trial mixture gradation: 25% RAP.

BATCHING SHEET

USE FOR RAP WT

U OF M MIX w/25% RAP BATCH WT = 15,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	30.0	25.0	20.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3750.0 wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3972.5 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	375.0	0.0	0.0	0.0	0.0	397.2 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	1500.0	0.0	0.0	0.0	750.0	0.0	0.0	0.0	0.0	794.5 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	45.0	862.5	0.0	0.0	0.0	450.0	0.0	0.0	0.0	0.0	476.7 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	90.0	1275.0	30.0	0.0	0.0	825.0	0.0	0.0	0.0	0.0	873.9 =#4
#4 - #8	4.75 - 2.38 mm	0.0	315.0	75.0	720.0	0.0	0.0	1350.0	0.0	0.0	0.0	0.0	1430.1 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	540.0	0.0	810.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	1080.0	0.0	450.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	1215.0	0.0	420.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	900.0	0.0	390.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	180.0	0.0	90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PAN	PAN	0.0	135.0	37.5	90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	TOTAL	0.00	4500.00	3750.00	3000.00	0.00	0.00	3750.00	0.00	0.00	0.00	0.00	15000.00
	TOTAL MINUS #4	0.0	4365.0	112.5	2970.0	0.0	0.0	1350.0	0.0	0.0	0.0	0.0	8797.5
	TOTAL MINUS #8	0.0	4050.0	37.5	2250.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6337.5

Calculate gms of AC for batch				
% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	856.2		222.5	633.8
	0.0			
	0.0			

Batching sheet for 15,000 gram mix: 25% RAP.

BATCHING SHEET

U OF M MIX w/25% RAP													
BATCH WT = 10,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	30.0	25.0	20.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2500.0 wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2648.3 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	250.0	0.0	0.0	0.0	0.0	264.8 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	1000.0	0.0	0.0	0.0	500.0	0.0	0.0	0.0	0.0	529.7 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	30.0	575.0	0.0	0.0	0.0	300.0	0.0	0.0	0.0	0.0	317.8 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	60.0	850.0	20.0	0.0	0.0	550.0	0.0	0.0	0.0	0.0	582.6 = #4
#4 - #8	4.75 - 2.38 mm	0.0	210.0	50.0	480.0	0.0	0.0	900.0	0.0	0.0	0.0	0.0	953.4 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	360.0	0.0	540.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	720.0	0.0	300.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	810.0	0.0	280.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	600.0	0.0	260.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	120.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PAN	PAN	0.0	90.0	25.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	TOTAL	0.00	3000.00	2500.00	2000.00	0.00	0.00	2500.00	0.00	0.00	0.00	0.00	10000.00
	TOTAL MINUS #4	0.0	2910.0	75.0	1980.0	0.0	0.0	900.0	0.0	0.0	0.0	0.0	5865.0
	TOTAL MINUS #8	0.0	2700.0	25.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4225.0

Calculate gms of AC for batch

% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	570.8		148.3	422.5
	0.0			
	0.0			

Batching sheet for 10,000 gram mix: 25% RAP.

Date: 02/14/11

Agency:

BATCHING SHEET

Location:

Trial Mix: U OF M MIX w/40% RAP

	50.0	37.50	25	19	12.5	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075	
Material	**2"**	**1 1/2"**	**1"**	**3/4**	**1/2**	**3/8**	**#4**	**#8**	**#16**	**#30**	**#50**	**100**	**#200**	%Ins
rap	100.0	100.0	100.0	100.0	94.0	87.0	69.0	55.0	44.0	32.0	18.0	10.0	6.6	
scandia screen sa	100.0	100.0	100.0	100.0	100.0	99.0	97.0	90.0	78.0	54.0	27.0	7.0	3.0	100
3/4 kram cle	100.0	100.0	100.0	100.0	60.0	37.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	100
limesand	100.0	100.0	100.0	100.0	100.0	100.0	99.0	75.0	48.0	33.0	19.0	6.0	3.0	100
Om Toss	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	85.0	65.0	49.0	35.0	24.1	100
KRMoss	100.0	100.0	100.0	100.0	100.0	100.0	98.0	97.0	81.0	61.0	52.0	40.0	30.9	
coarse rap	**100.0**	**100.0**	**100.0**	**90.0**	**70.0**	**58.0**	**36.0**							
g														
h														
i														
j														

VMA	Max Size	Air Voids
37.00	0.75	4.00

target AC= **5.40**

For Recycled Mixtures; Asphalt Conte **5.60**

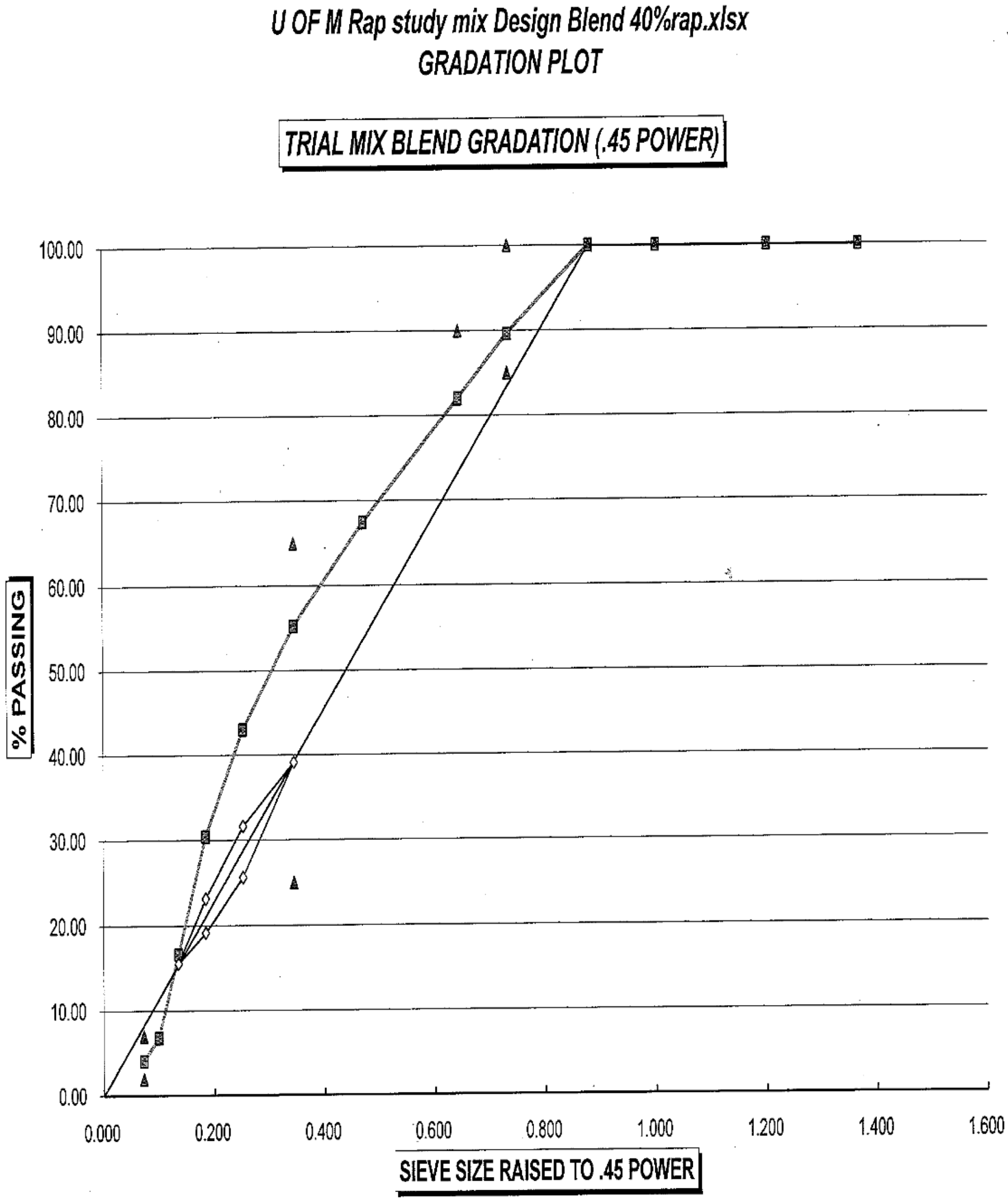
shingle AC= **0.00**

25.00 **Approxmiate VMA Trail Seed Values: 50mm 39, 37.5mm 38, 25mm 37.5, 19mm 37, 12.5mm 36.5 etc**

Cost	Cost	**Trial**	**50.0**	**37.50**	**25**	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.60**	**0.30**	**0.15**	**0.075**	
Cal.	Mat's	%	**2"**	**1 1/2"**	**1"**	**3/4**	**1/2**	**3/8**	**#4**	**#8**	**#16**	**#30**	**#50**	**100**	**#200**	
0.00	rap	**40**	40	40	40	40	38	35	28	22	18	13	7	4	3	0.0
0.00	;reen sa	**20**	20	20	20	20	20	20	19	18	16	11	5	1	1	4.5
0.00	ım clear	**20**	20	20	20	20	12	7	1	0	0	0	0	0	0	44.2
0.00	mesand	**20**	20	20	20	20	20	20	20	15	10	7	4	1	1	11.2
0.00	)m Toss	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	KRMoss	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	arse rap	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		**100.0**														
		JMF =	**100.0**	**100.0**	**100.0**	**100.0**	**89.6**	**82.0**	**67.4**	**55.2**	**43.0**	**30.4**	**16.6**	**6.8**	**4.0**	
		C Pts	100	100	100	100	85	35	30	25					2	
			100	100	100	100	100	90	80	65					7	
		Restricted								39.1	26	19	16			
		Zone								39.1	32	23	16			

C:\Documents and Settings\line1dav\My Documents\U OF M Rap study mix Design Blend 40%rap.xlsx 3.6

Design sheet for 40% RAP.



Trial mixture gradation: 40% RAP.

BATCHING SHEET

U OF M MIX w/40% RAP BATCH WT = 10,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j		
SIEVE SIZE (PASSING - RETAINED)		0.0	20.0	20.0	20.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	adjusted RAP wt	
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4000.0	wt % of bat
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4237.3	adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	423.7	=3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	800.0	0.0	0.0	0.0	800.0	0.0	0.0	0.0	0.0	847.5	=1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	20.0	460.0	0.0	0.0	0.0	480.0	0.0	0.0	0.0	0.0	508.5	=3/8
3/8" - #4	9.5 - 4.75 mm	0.0	40.0	680.0	20.0	0.0	0.0	880.0	0.0	0.0	0.0	0.0	932.2	= #4
#4 - #8	4.75 - 2.38 mm	0.0	140.0	40.0	480.0	0.0	0.0	1440.0	0.0	0.0	0.0	0.0	1525.4	= minus#4
#8 - #16	2.38 - 1.16 mm	0.0	240.0	0.0	540.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#16 - #30	1.16 - 0.60 mm	0.0	480.0	0.0	300.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#30 - #50	0.60 - 0.30 mm	0.0	540.0	0.0	280.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#50 - #100	0.30 - 0.15 mm	0.0	400.0	0.0	260.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#100 - #200	0.15 - 0.075mm	0.0	80.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
PAN	PAN	0.0	60.0	20.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
	TOTAL	0.00	2000.00	2000.00	2000.00	0.00	0.00	4000.00	0.00	0.00	0.00	0.00	10000.00	
	TOTAL MINUS #4	0.0	1940.0	60.0	1980.0	0.0	0.0	1440.0	0.0	0.0	0.0	0.0	5420.0	
	TOTAL MINUS #8	0.0	1800.0	20.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3320.0	

Calculate gms of AC for batch

% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	570.8		237.3	333.5
	0.0			
	0.0			

Batching sheet for 15,000 gram mix: 40% RAP.

BATCHING SHEET

U OF M MIX w/40% RAP													
BATCH WT = 10,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	20.0	20.0	20.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4000.0 wt % of bat
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4237.3 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	423.7 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	800.0	0.0	0.0	0.0	800.0	0.0	0.0	0.0	0.0	847.5 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	20.0	460.0	0.0	0.0	0.0	480.0	0.0	0.0	0.0	0.0	508.5 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	40.0	680.0	20.0	0.0	0.0	880.0	0.0	0.0	0.0	0.0	932.2 = #4
#4 - #8	4.75 - 2.38 mm	0.0	140.0	40.0	480.0	0.0	0.0	1440.0	0.0	0.0	0.0	0.0	1525.4 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	240.0	0.0	540.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	480.0	0.0	300.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	540.0	0.0	280.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	400.0	0.0	260.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	80.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PAN	PAN	0.0	60.0	20.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	TOTAL	0.00	2000.00	2000.00	2000.00	0.00	0.00	4000.00	0.00	0.00	0.00	0.00	10000.00
	TOTAL MINUS #4	0.0	1940.0	60.0	1980.0	0.0	0.0	1440.0	0.0	0.0	0.0	0.0	5420.0
	TOTAL MINUS #8	0.0	1800.0	20.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3320.0

Calculate gms of AC for batch				
% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	570.8		237.3	333.5
	0.0			
	0.0			

Batching sheet for 10,000 gram mix: 40% RAP.

Date: 02/10/11

Agency:

BATCHING SHEET

Trial Mix: U OF M MIX w/55% RAP

Material	50.0 2"	37.50 1 1/2"	25 1"	19 3/4	12.5 1/2	9.5 3/8	4.75 #4	2.36 #8	1.18 #16	0.60 #30	0.30 #50	0.15 100	0.075 #200	%Ins
rap	100.0	100.0	100.0	100.0	94.0	87.0	69.0	55.0	44.0	32.0	18.0	10.0	6.6	
scandia screen sa	100.0	100.0	100.0	100.0	100.0	99.0	97.0	90.0	78.0	54.0	27.0	7.0	3.0	100
3/4 kram cle	100.0	100.0	100.0	100.0	60.0	37.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	100
limesand	100.0	100.0	100.0	100.0	100.0	100.0	99.0	75.0	48.0	33.0	19.0	6.0	3.0	100
Om Toss	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	85.0	65.0	49.0	35.0	24.1	100
KRMoss	100.0	100.0	100.0	100.0	100.0	100.0	98.0	97.0	81.0	61.0	52.0	40.0	30.9	
coarse rap	100.0	100.0	100.0	90.0	70.0	58.0	36.0							
g														
h														
i														
j														

VMA	Max Size	Air Voids
37.00	0.75	4.00

target AC= 5.40

For Recycled Mixtures; Asphalt Conte 5.60

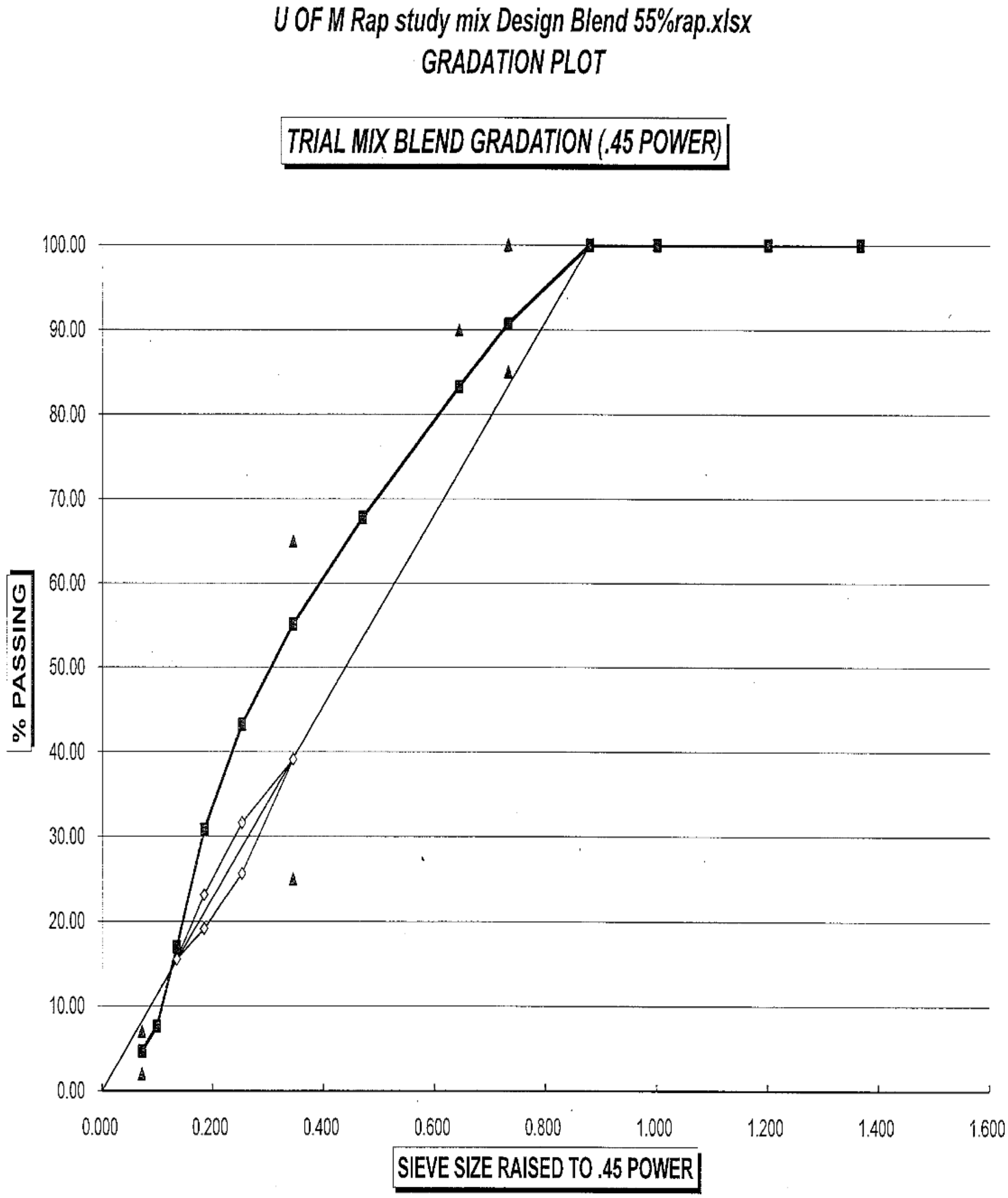
shingle AC= 0.00

25.00 Approxmiate VMA Trail Seed Values: 50mm 39, 37.5mm 38, 25mm 37.5, 19mm 37, 12.5mm 36.5 etc

Cost Cal.	Cost Mat's	Trial %	50.0 2"	37.50 1 1/2"	25 1"	19 3/4	12.5 1/2	9.5 3/8	4.75 #4	2.36 #8	1.18 #16	0.60 #30	0.30 #50	0.15 100	0.075 #200	
0.00	rap	55	55	55	55	55	52	48	38	30	24	18	10	6	4	0.0
0.00	:reen sa	15	15	15	15	15	15	15	15	14	12	8	4	1	0	3.3
0.00	am clear	15	15	15	15	15	9	6	0	0	0	0	0	0	0	33.1
0.00	mesand	15	15	15	15	15	15	15	15	11	7	5	3	1	0	8.4
0.00	)m Toss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	KRMoss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00	arse rap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.00		100.0														
		JMF =	100.0	100.0	100.0	100.0	90.7	83.3	67.8	55.2	43.3	30.8	17.0	7.6	4.7	
		C Pts	100	100	100	100	85	35	30	25					2	
			100	100	100	100	100	90	80	65					7	
		Restricted								39.1	26	19	16			
		Zone								39.1	32	23	16			
		TARGET GRAD				100	89	81	67	56	44	31	17	6	3.6	

C:\Documents and Settings\line1dav\My Documents\U OF M Rap study mix Design Blend 55%rap.xlsx

Design sheet for 55% RAP.



Trial mixture gradation: 55% RAP.

BATCHING SHEET

USE FOR RAP WT

U OF M MIX w/55% RAP BATCH WT = 15,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j	
SIEVE SIZE (PASSING - RETAINED)		0.0	15.0	15.0	15.0	0.0	0.0	55.0	0.0	0.0	0.0	0.0	adjusted RAP wt
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8250.0 wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8739.4 adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	825.0	0.0	0.0	0.0	0.0	873.9 =3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	900.0	0.0	0.0	0.0	1650.0	0.0	0.0	0.0	0.0	1747.9 =1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	22.5	517.5	0.0	0.0	0.0	990.0	0.0	0.0	0.0	0.0	1048.7 =3/8
3/8" - #4	9.5 - 4.75 mm	0.0	45.0	765.0	22.5	0.0	0.0	1815.0	0.0	0.0	0.0	0.0	1922.7 = #4
#4 - #8	4.75 - 2.38 mm	0.0	157.5	45.0	540.0	0.0	0.0	2970.0	0.0	0.0	0.0	0.0	3146.2 = minus#4
#8 - #16	2.38 - 1.16 mm	0.0	270.0	0.0	607.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#16 - #30	1.16 - 0.60 mm	0.0	540.0	0.0	337.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#30 - #50	0.60 - 0.30 mm	0.0	607.5	0.0	315.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#50 - #100	0.30 - 0.15 mm	0.0	450.0	0.0	292.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#100 - #200	0.15 - 0.075mm	0.0	90.0	0.0	67.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PAN	PAN	0.0	67.5	22.5	67.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	TOTAL	0.00	2250.00	2250.00	2250.00	0.00	0.00	8250.00	0.00	0.00	0.00	0.00	15000.00
	TOTAL MINUS #4	0.0	2182.5	67.5	2227.5	0.0	0.0	2970.0	0.0	0.0	0.0	0.0	7447.5
	TOTAL MINUS #8	0.0	2025.0	22.5	1687.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3735.0

Calculate gms of AC for batch

% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	856.2		489.4	366.8
	0.0			
	0.0			

Batching sheet for 15,000 gram mix: 55% RAP.

BATCHING SHEET

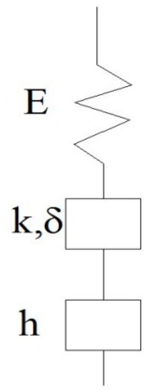
U OF M MIX w/55% RAP BATCH WT = 10,000		rap	screen sa	3/4 kram clear	limesand	Om Toss	KRMoss	coarse rap	g	h	i	j		
SIEVE SIZE (PASSING - RETAINED)		0.0	15.0	15.0	15.0	0.0	0.0	55.0	0.0	0.0	0.0	0.0	adjusted RAP wt	
2" - 1 1/2"	50.0 - 37.5 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5500.0	wt % of ba
1 1/2" - 1"	37.5 - 25.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5826.3	adj rap wt
1" - 3/4"	25.0 - 19.0 mm	0.0	0.0	0.0	0.0	0.0	0.0	550.0	0.0	0.0	0.0	0.0	582.6	=3/4
3/4" - 1/2"	19.0 - 12.5 mm	0.0	0.0	600.0	0.0	0.0	0.0	1100.0	0.0	0.0	0.0	0.0	1165.3	=1/2
1/2" - 3/8"	12.5 - 9.5 mm	0.0	15.0	345.0	0.0	0.0	0.0	660.0	0.0	0.0	0.0	0.0	699.2	=3/8
3/8" - #4	9.5 - 4.75 mm	0.0	30.0	510.0	15.0	0.0	0.0	1210.0	0.0	0.0	0.0	0.0	1281.8	= #4
#4 - #8	4.75 - 2.38 mm	0.0	105.0	30.0	360.0	0.0	0.0	1980.0	0.0	0.0	0.0	0.0	2097.5	= minus#4
#8 - #16	2.38 - 1.16 mm	0.0	180.0	0.0	405.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#16 - #30	1.16 - 0.60 mm	0.0	360.0	0.0	225.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#30 - #50	0.60 - 0.30 mm	0.0	405.0	0.0	210.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#50 - #100	0.30 - 0.15 mm	0.0	300.0	0.0	195.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
#100 - #200	0.15 - 0.075mm	0.0	60.0	0.0	45.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
PAN	PAN	0.0	45.0	15.0	45.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
	TOTAL	0.00	1500.00	1500.00	1500.00	0.00	0.00	5500.00	0.00	0.00	0.00	0.00	10000.00	
	TOTAL MINUS #4	0.0	1455.0	45.0	1485.0	0.0	0.0	1980.0	0.0	0.0	0.0	0.0	4965.0	
	TOTAL MINUS #8	0.0	1350.0	15.0	1125.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2490.0	

Calculate gms of AC for batch				
% AC (Mix)	total AC gms		RAP AC	new add AC
	0.0			
5.40	570.8		326.3	244.6
	0.0			
	0.0			

Batching sheet for 10,000 gram mix: 55% RAP.

Appendix D: An Introduction to Back-calculating Creep Compliance and Creep Stiffness from IDT Mixture Testing using the Huet Model and ENTPE Transformation

Huet model (following figure) and *ENTPE* transformation were used to back-calculate creep compliance, *D(t)* and its inverse creep stiffness, *S(t)*, of asphalt binder from IDT mixture results. More details about the *Huet* model and *ENTPE* transformation can be found in referenced documents (11, 12, 13).



Huet Model.

Creep stiffness, a known value determined from IDT testing, is inverse to creep compliance. In *Huet* model (*1*) the creep compliance *D(t)*, is calculated as follows:

$$D(t) = \frac{1}{E_\infty}\left(1 + \delta \frac{(t/\tau)^k}{\Gamma(k+1)} + \frac{(t/\tau)^h}{\Gamma(h+1)}\right)$$

Equation 1

where:

i = complex number (i^2=-1);
E_∞ = glassy modulus;
h, k = exponents, $0 < k < h < 1$;
δ = dimensionless constant;
ω = 2π*frequency;
τ = characteristic time varying with temperature accounting for the Time Temperature Superposition Principle (TTSP), $\tau = a_T(T)\cdot\tau_0(T_S)$;
a_T = shift factor at temperature T
τ_0 = characteristic time determined at reference temperature T_S
Γ = gamma function which can be expressed as follows:

$$\Gamma(n) = \int_0^\infty t^{n-1}e^{-t}dt$$

Equation 2

$$\Gamma(n+1) = n\Gamma(n)$$

Equation 3

$n > 0$ or Real $(n) > 0$
t integration variable
n argument of the gamma function.

An expression that relates asphalt mixture and asphalt binder creep stiffness, referred to as *ENTPE* transformation, was recently proposed by *Cannone Falchetto et al.* (14) based on *Huet* model:

$$S_{mixture}(t) = S_{binder}(t \cdot 10^{-\alpha}) \cdot \frac{E_{\infty mixture}}{E_{\infty binder}}$$

Equation 4

where:

α = a regression coefficient depending on mixture type and binder aging.

The inverse relation that expresses binder stiffness as a function of mixture stiffness can be easily obtained:

$$S_{binder}(t) = S_{mixture}(t \cdot 10^{\alpha}) \cdot \frac{E_{\infty binder}}{E_{\infty mixture}}$$

Equation 5

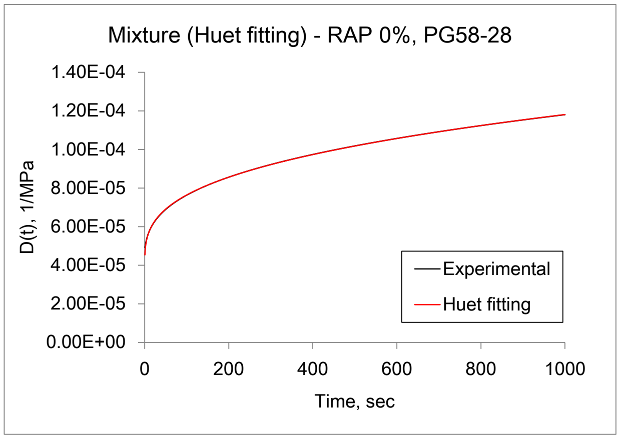
Back-calculation Results

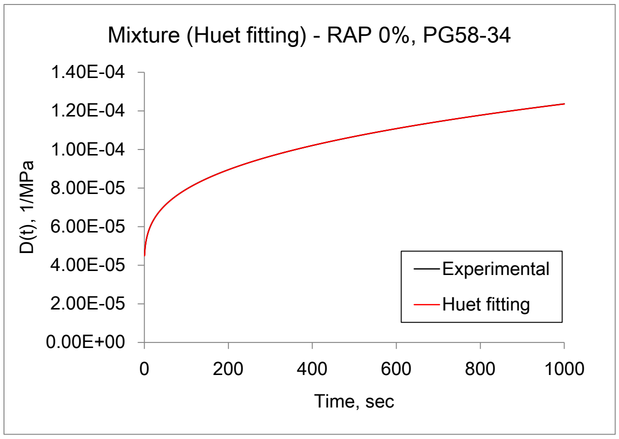
The values of the model parameters obtained from fitting the IDT mixture data are summarized in the table.

Table Summary of Parameters from IDT Mixture Tests at PG + 10ºC

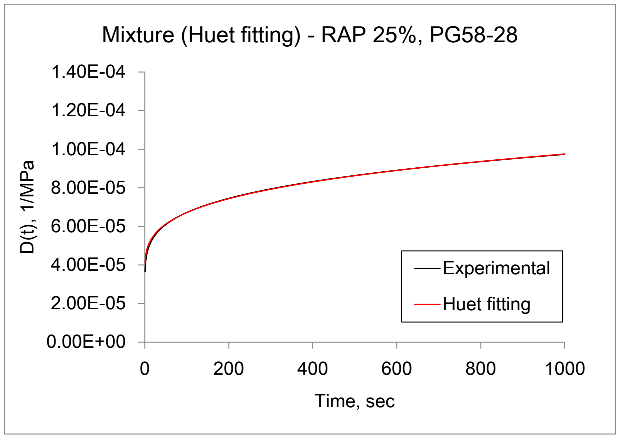
Binder	RAP, %	T, ºC	E_∞, MPa	h	k	δ	τ_{mix}
58-28	0	-18ºC	30000	0.4707	0.1930	1.3192	1024.000
	25		30000	0.2871	0.2664	0.7459	1023.293
	40		29046	0.2620	0.2610	0.2996	1328.885
	55		30000	0.2784	0.2774	0.2619	1514.684
58-34	0	-24ºC	30000	0.3925	0.2530	1.5440	1479.108
	25		30000	0.2713	0.2703	0.7299	1678.042
	40		30000	0.2400	0.2390	0.2505	2223.980
	55		30000	0.2582	0.2572	0.2248	2464.588

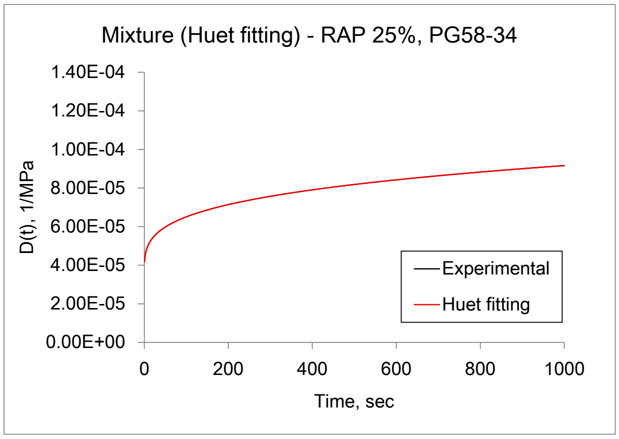
Examples of model fitting are shown in the figures below. It can be seen that *Huet* model provided a very good fit of the experimental mixture data.



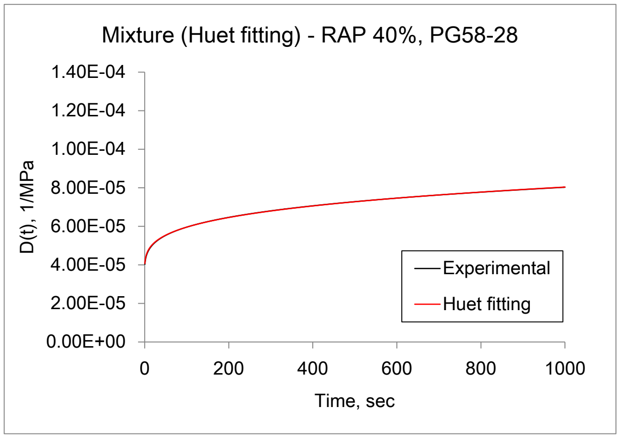


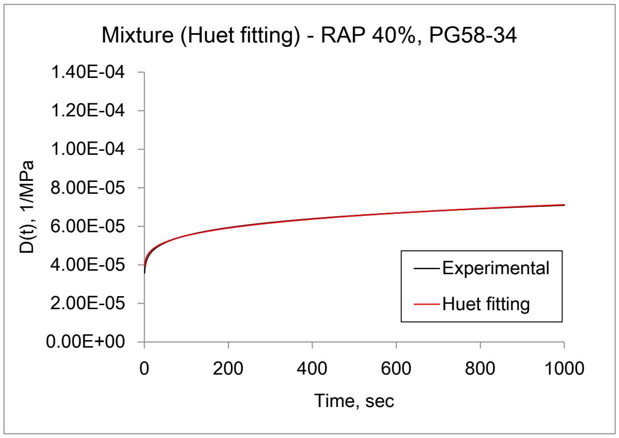
Huet Model for 0% RAP Mixtures.



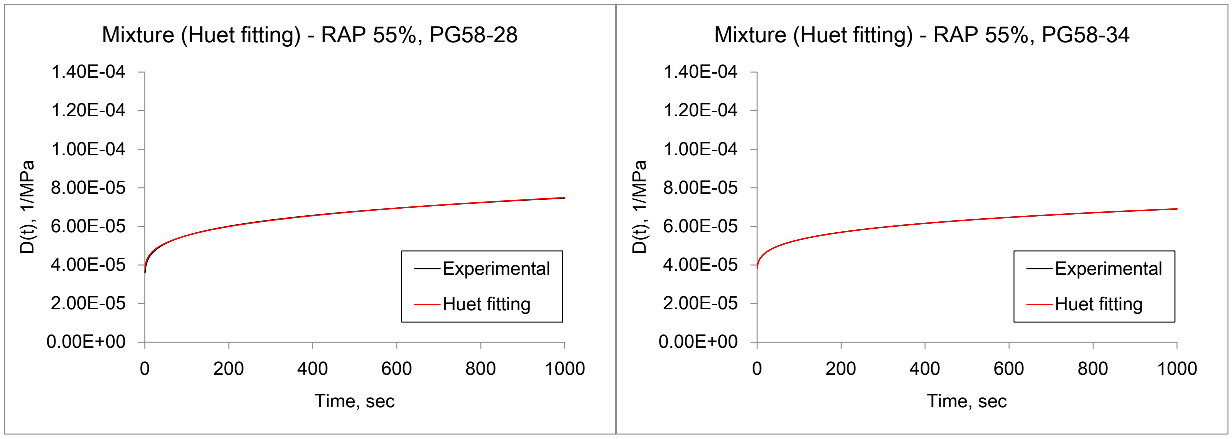


Huet Model for 25% RAP Mixtures.





Huet Model for 40% RAP Mixtures.

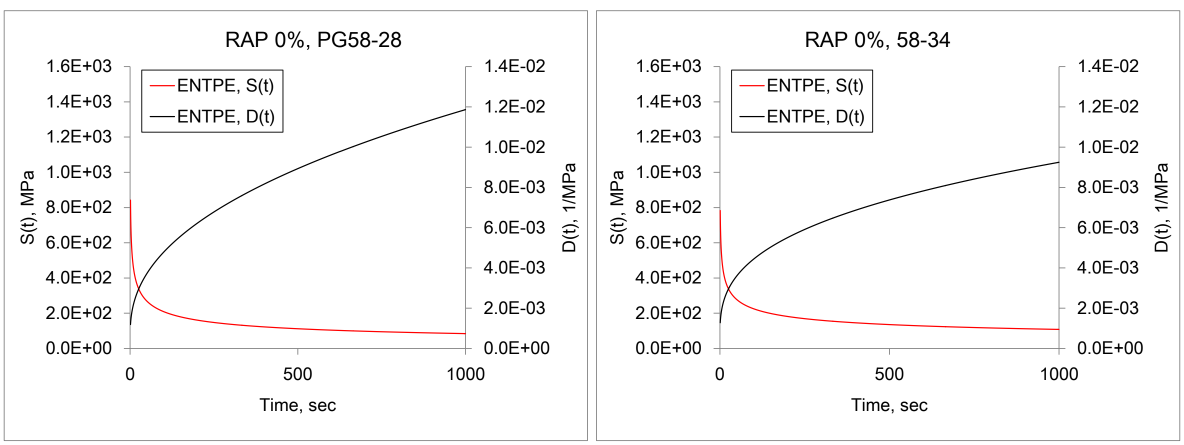


Huet Model for 55% RAP Mixtures.

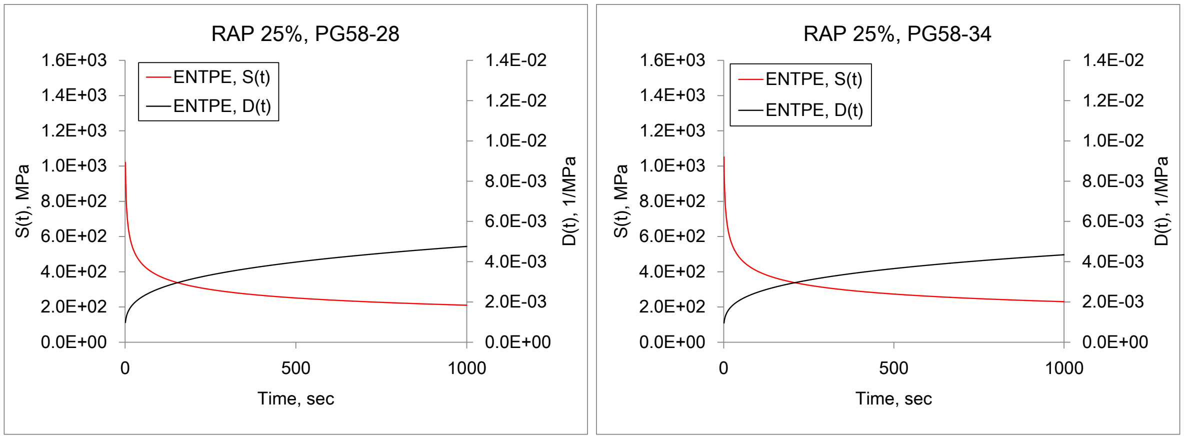
To back-calculate binder properties, two more parameters, α and $E_{\infty\text{-}binder}$, are needed. The following values were assumed based on results obtained in a previous study by Di Benedetto (13):

- α = 3.01 for PG 58-28 binder and α = 3.17 for PG 58-34 binder
- Glassy modulus of binder ($E_{\infty\text{-}binder}$) was assumed 3 GPa

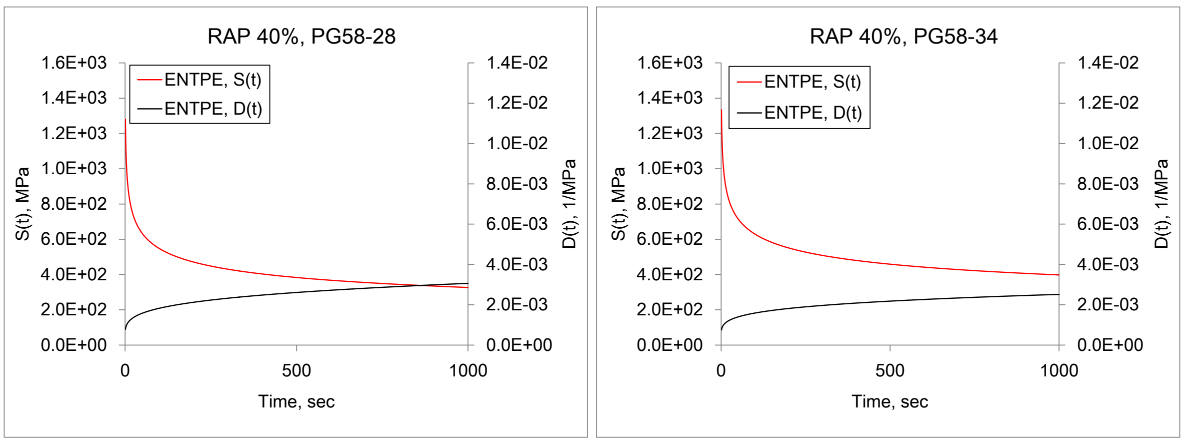
The results of creep stiffness, *S(t)*, and creep compliance, *D(t)*, of asphalt binders are shown in the following figures.



Predicted Asphalt Binder S(t) and D(t) from 0% RAP Mixtures.



Predicted Asphalt Binder S(t) and D(t) from 25% RAP Mixtures.



Predicted Asphalt Binder S(t) and D(t) from 40% RAP Mixtures.

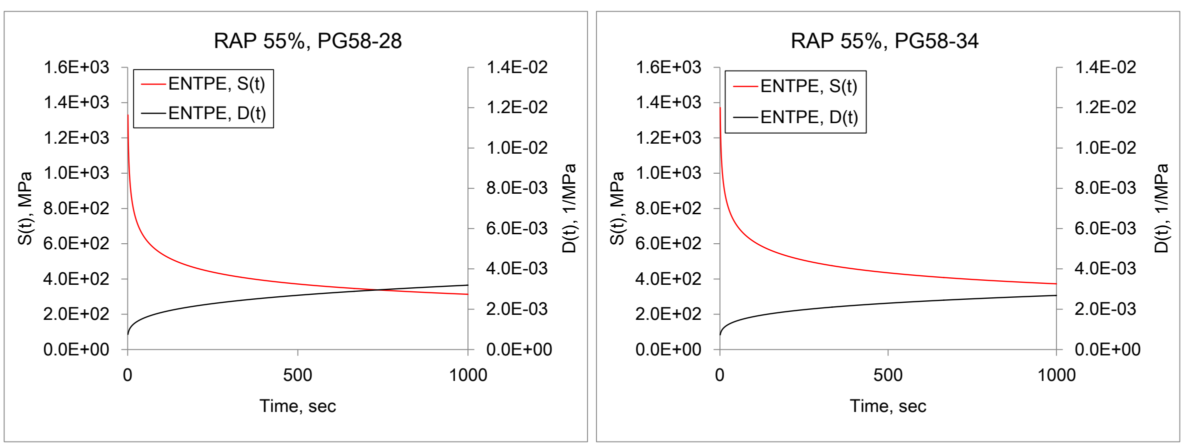


Figure Predicted Asphalt Binder S(t) and D(t) from 55% RAP Mixtures.

The back-calculated binder stiffness, S(60s) and S(500s), are shown in the following table.

Back-calculated Asphalt Binder Stiffness, S(60s) and S(500s)

Binder	RAP, %	T, ºC	S(60s), MPa	S(500s), MPa
58-28	0	-18ºC	251	112
	25		425	251
	40		609	383
	55		609	371
58-34	0	-24ºC	262	136
	25		453	273
	40		692	459
	55		679	435